RPSEA

Wax Control in the Presence of Hydrates

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Project Title

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Abstract

This project consisted of an examination of technologies for minimizing or preventing wax formation in long-distance uninsulated tiebacks. The literature review conducted in Phase I revealed that cold flow was a promising technology. In cold flow, the oil is cooled to the ambient temperature with the intent of minimizing or eliminating the thermal flux that causes wax deposition. It was also found that pigging will always be used as a backup and targeted chemical treatments will be needed. An experimental investigation of cold flow was conducted in Phase II. Experiments conducted at different cold flow conditions confirmed that the deposition is minimized under cold flow conditions. The experimental program consisted of formulating the necessary and appropriate model oils, designing a novel dual-loop flow loop system and conceptualizing and manufacturing a scraped heat exchanger for slurry creation. Apart from confirming the validity of the cold flow system, experiments were also conducted to examine restart under cold flow conditions. It was revealed that a small heat flux also prevents deposition. This was due to the suppression of cloud point caused by taking wax out of solution. The restart experiments revealed that restart pressures are lower under cold flow conditions.

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Executive Summary

In Phase I of this project, technologies for enabling transport of crude oil under cold flow environments were examined. The focus was on finding game-changing technologies using single uninsulated tiebacks and/or export lines. Technologies capable of handling both the hydrate and wax deposition problems at the same time are needed to extend subsea tiebacks and to exploit marginal fields further offshore. Literature review and discussions with the industrial steering committee revealed that there were a number of wax-related issues, which needed to be addressed first. Therefore, the scope of this project was limited to wax deposition issues.

The concept of cold flow has been proposed and discussed in a few papers recently. In this approach, the flowing steam is cooled to seawater temperatures, and is seeded with hydrates and/or wax particles. The increased deposition area internal to the flow and significant reduction of the radial thermal flux are considered responsible for reducing deposition on pipeline walls. Bench-scale experiments have demonstrated the effectiveness of the concept for hydrates, waxy oils and in cases involving the formation of both hydrates and waxes. In terms of fundamental basis for the technology and range of applicability, cold flow is further along for hydrates than for wax. In comprehensive DeepStar reports, questions concerning the applicability of wax cold flow technology and the economics of transporting slurries have been raised. There is also a need to answer fundamental questions concerning slurry creation, particle morphology, and mixture rheology. Even so, cold flow is one of the technologies that might make long-distance uninsulated tiebacks possible in deepwater and is being considered for further evaluation.

Pigging technologies are critical for pipeline management in deepwater. There have been a number of advances in pigging technologies including pigs capable of crawling upstream. These types of pigs and subsea pig launching schemes are expected to provide the necessary backup for commercial implementation of cold flow technologies.

Three types of thermal management options are available. Insulation and active heating are currently being used, but are expensive. In-situ heat and gas generation methods (by using chemicals causing an exothermic reaction) are not likely to be applicable in the deepwater offshore United States due to types of chemicals involved and due to other control issues.

Chemical injection has also been used as a wax/hydrate mitigation strategy. The science and practice of chemical injection is advanced. However, the mitigation strategies are typically designed to address specific chemical compositions and conditions. Very few studies address mitigating waxes and hydrates at the same time. It is unlikely that an inexpensive chemical injection strategy could be used to design cold flow. Targeted chemical injection would always be part of the total solution.

Different types of coatings have been proposed for preventing or minimizing deposition. The flowing conditions also impact deposition. We found that, in general, coatings are not effective in preventing deposition and will not be applicable to cold flow.

The literature review revealed that the solution to wax-hydrate problems is multipronged, and often back-up strategies are required. The literature is consistent in assessing that cold flow reduces depositions in the case of wax, hydrates, and in wax-hydrate mixtures. A chemical-only solution to the wax problem is unlikely. Coatings have not been effective for the most part and sonic, magnetic and biodegradation methods need significant development.

We decided to focus the experimental investigations in Phase II of the project on cold flow involving wax based on the steering committee recommendation. The research program consisted of the following elements:

- Formulation of model oil systems for the cold flow study: Model oil with wax appearance temperature (WAT) sufficiently different from the pour point was designed using two different waxes and a mineral oil.
- Measurements of the properties of interest: Density, viscosity, WAT, pour point, and other properties of relevance were measured.
- Cold flow transport fundamental analysis and experimental validation: The fundamental theory of cold flow (namely, no deposition with zero thermal flux) was verified under different flow and flux conditions.
    - No deposition was observed under nearly cold flow conditions as well. A hypothesis was raised at the RPSEA Technology Transfer Meetings about the cloud-point suppression of the test fluid due to precipitation of waxes on the reservoir cold coils. We proved this hypothesis by conducting a cloud-point suppression study.
- Mechanical aspects of slurry makers since creating the slurry would be a big part of implementing cold flow in a practical sense: A scraped heat exchanger was designed and built to make wax slurries.
- Observation of wax particles from the loop: A particle visualization system was placed in the flow loop to observe particles and to measure particle size.
- Restart under cold flow conditions: Restart under cold flow conditions was performed, and it was shown that the gel formed under the cold flow conditions is weaker than the gel formed at the same temperature under “hot flow” conditions.

Background

The purpose of this project was to develop a fundamental understanding of alternatives for preventing wax formation in deep water, uninsulated subsea pipelines. This project involved two phases: (1) a comprehensive literature review concerning technologies to attain oil transport in uninsulated subsea pipelines; and (2) an experimental evaluation of the most promising technologies/concepts based on the review.

Unique challenges are associated with transporting hydrocarbon fluids through long subsea pipelines associated with deepwater oil and gas production. Wax precipitation in these flow lines due to the cold temperatures is a serious problem. One way of preventing wax precipitation in long subsea lines is to insulate them, an expensive solution. A number of other wax-control technologies have been proposed, some of which are being employed commercially. These include mechanical methods such as pigging, chemical injection technologies, and thermal management strategies, which focus on preventing the problem. One concept that has been tested recently but has not been implemented commercially is a process termed "cold flow." The idea is to engineer a controlled formation of slurry made-up wax and/or hydrate particles. The idea was to manage the flow of oil-water mixtures in the presence of this slurry. One of the key components of the technology is to eliminate or minimize the thermal flux between the flowing oil and the ambient environment. This is very much possible in the Gulf of Mexico conditions where the sea temperature tends to be about 4°C. In addition, the seed particles in the slurry act as nucleation sites and prevent or minimize further wax deposition in areas that might restrict flow.

In previous studies, no single strategy had proven to be completely effective in preventing and/or remediating the problem. There was a need to carefully evaluate all available technologies and select the most promising for further evaluation. The purpose of this study was to identify gaps and challenges, associated with each option for preventing wax precipitation in uninsulated pipelines. The general approach was to look at broad classes of technologies: mechanical methods (e.g., cold seeding, sonic methods, scrapers (pigs), internal pipe coatings, coiled tubing services, etc.), chemical methods (e.g., inhibitor and solvent injections to prevent or minimize the rate of wax deposit accumulation), and thermal management techniques (which provide the necessary heat input to prevent deposition).

Technology Review

Each of the technologies described in the next few sections consists of the following elements.

- Description of the technology and how it works
- Technical gaps

- The state of development of the technology and its availability
- Effectiveness of the technology, when used in a cold flow deepwater subsea application
- Review of literature

Cold Flow

The deposition of the wax and/or hydrates consists of two separate, but interdependent components – precipitation and deposition. Precipitation is primarily controlled by thermodynamics, while deposition is impacted by heat, mass and momentum transfer processes. Cold flow takes advantage of the fact that while there may be solids present in the liquid being transported, driving forces for the deposition of these solids are either minimized or eliminated. The concept of cold seeding is illustrated in Figure 1. The oil is cooled to temperatures around the seawater temperature in a mechanical device. Generally, the WAT of the oil is greater than the seawater temperature. As a result, a certain amount of wax precipitates in the device. The solids formed are then transported as slurry along with the associated liquid. With the fluid temperature equal or near the seawater temperature, the presence of thermal flux is minimized or eliminated. This thermal flux is considered the main driving force for wax deposition, leading to a belief that further deposition in the pipeline would be minimized. Furthermore, the WAT of the liquid is likely to be lower in comparison to that of the original oil because the heaviest paraffinic components are out of solution.

Detailed studies of cold seeding for waxy oils were reported in the DeepStar Report 4202-b2. Nenniger Engineering, Inc. (NEI) designed and built an apparatus to collect wax deposits in the laboratory and to test the seeding concept. The seed dose provided a particulate surface area of four times the wall area. An 80 percent reduction in wax deposition rates was observed. At lower temperatures, the inventory of naturally occurring suspended waxy solids increased in the oil, and the seeds became less effective. In the proof-of-concept testing phase of this project, synthetic seeding (polyethylene powder) was employed.

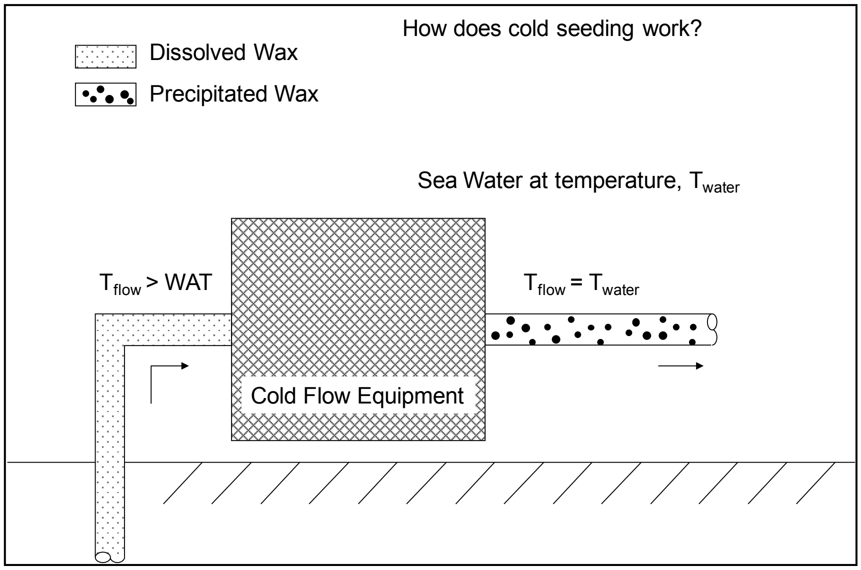


Figure 1: The concept of cold seeding is to cool the oil sufficiently to precipitate some solids and transport the resulting slurry in the pipeline. Several publications (Merino-Garcia and Correra, 2008) describe the mechanical device for making the cold slurry.

A prominent invention described in a patent is shown in Figure 2.

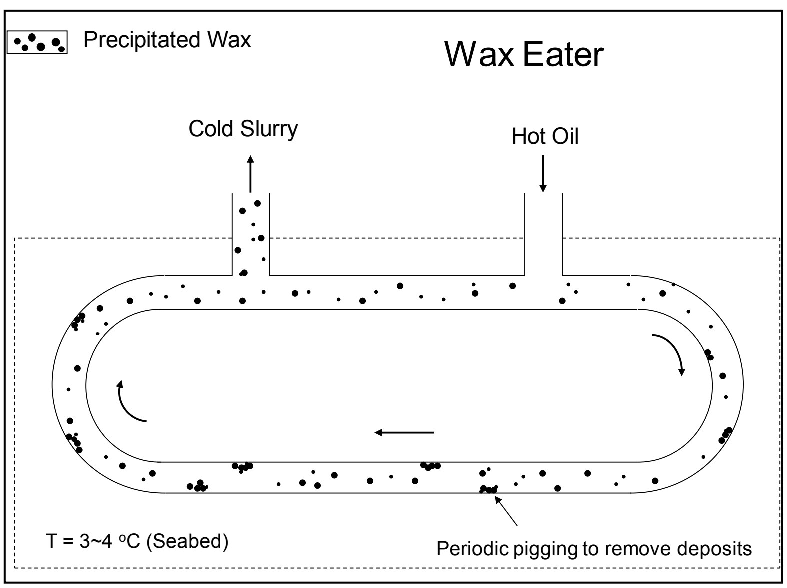


Figure 2: A concept for making the slurry in wax cold flow applications. The device was known as "Wax Eater."

In the "Wax Eater," the hot oil enters a loop that is maintained at colder temperatures to cause solids precipitation. A pig goes around the loop scraping the wax and placing it in slurry. The cold slurry is transported out of the loop. The mechanical operations of the loop, including the temperatures to which the incoming fluids are cooled, the ability of the pig to circulate and scrape the wax, etc. were cited as some issues that needed improvement.

Other cooling and wax-removal approaches have also been proposed and have been tested at various levels. High Shear Heat Exchanger (Fung, 2003) was proposed wherein the turbulence generated in the device was adequate to remove solids. No experimental evidence was available to understand the range of validity and limitations of this concept.

The concept of causing wax precipitation by the Joule-Thompson effect was proposed by Knowles, Jr. et. al. (1986). The concept is illustrated in Figure 3. The concept has not been tested extensively. High velocities at the point of constriction may be sufficient to disengage the formed wax and transport it as slurry.

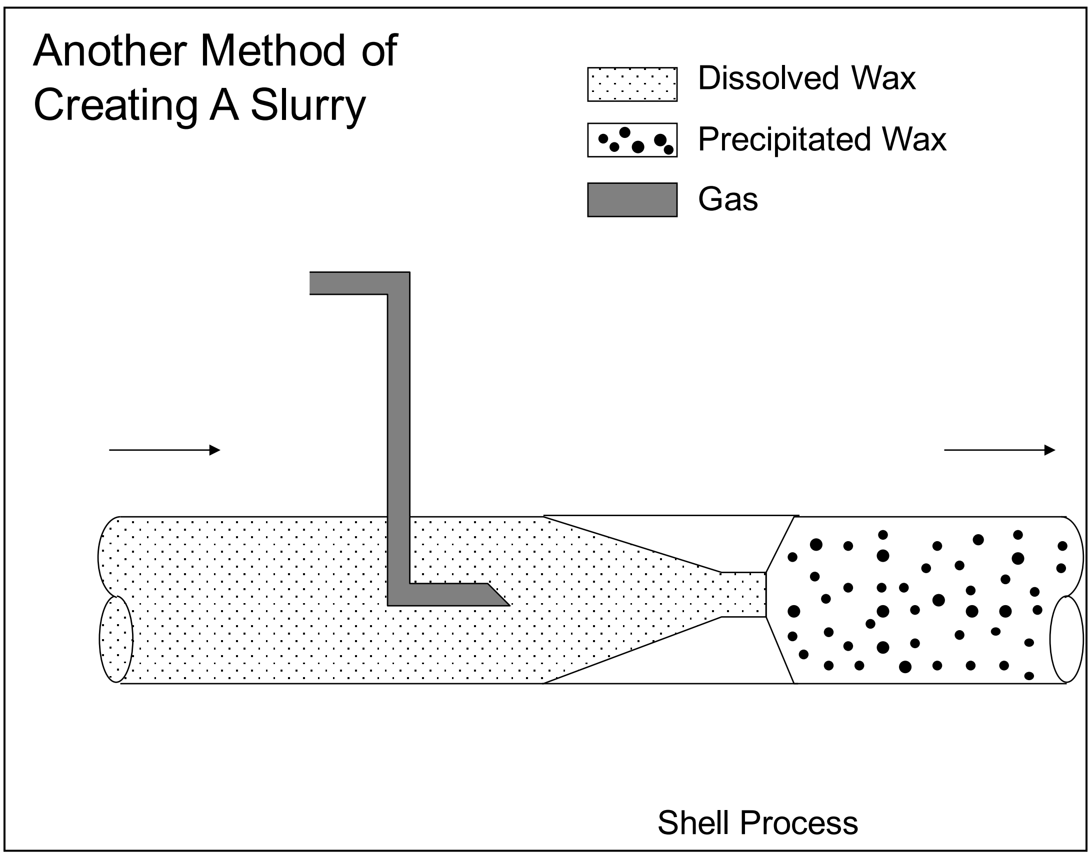


Figure 3: The flash cooling concept utilizing the Joule-Thompson effect to cause solids precipitation.

Cold Flow – Applied to Hydrates

Cold flow technology as applied to hydrates has been discussed in a number of papers and patents. Turner and Talley (2008) published a comprehensive paper on formation of hydrate slurries and on factors affecting the flow of slurries. Nonadhesive hydrate slurries were formed, and these exhibited reasonable viscosities in a flow loop when formed under certain conditions. They observed that the factors that favor formation of low-viscosity hydrate slurries include a high Reynolds number, and high mass-transfer and heat-transfer rates. The effects of other operational parameters like velocities and liquid loading were also examined. Mixing devices for the creation of appropriate slurries were also identified in this study. Hydrate slurry formation and some flow characteristics of the slurry have been reported by researchers at the Norwegian University of Science and Technology. Some of the basic particle-formation characteristics and rheological slurry properties required for transport were described by Andersson and Gudmundsson (1999). Excellent research on hydrates has been carried out over a long period of time at the Colorado School of Mines by Dr. Sloan and his group. In one of their recent publications (Boxall et. al., 2008), they described some new analytical procedures for characterizing hydrate particles.

Cold Flow – Applied to Hydrates and Wax

The concept of cold flow has also been proposed and tested to address hydrate problems. Lund et. al. (1999) created slurries consisting of hydrate particles. The particles act as seeds for particle growth preventing deposition and plugging of both wax and hydrates. The technology and applications to crude oils containing waxes and hydrates were patented by SINTEF and have been discussed in a number of publications and in some DeepStar reports. Larsen et. al. (2007) describe cold flow as a system in which hydrocarbon production fluids are flowing at thermodynamic equilibrium in uninsulated pipelines, without the help of chemical modifiers (thermodynamic or kinetic gas hydrate inhibitors, low-dosage anti-agglomerates, or wax modifiers), and without the help of active or passive heating or heat-retention schemes. The flowing slurry comprises inert particles (e.g., gas hydrates and/or wax particles). Numerous experiments were carried out. Their one-inch (1") diameter loop was operable with reconstituted well fluids and with an appropriate gas phase added to adjust hydrate equilibrium conditions. Several crude oils from different oil provinces around the world (Gulf of Mexico and West of Africa) were "cold flow" tested in this facility.

The baseline tests for wax and hydrate deposition were carried out first. About 0.6 wt percent of the total wax was deposited, and the maximum allowable water content in hydrate tests was 4 percent. In all the experiments, the seeds were already added to the cold fluid. The nature of the seeds, morphology, etc. was not reported. An order of magnitude reduction in wax deposition was observed under cold flow conditions. In experiments with hydrates and wax, a ten-fold increase in water handling capability was observed.

In summary, the cold flow hydrate technology appears to be further along than the cold flow wax technology. At the bench-scale, the technology has been demonstrated and appears applicable over a wide range. The scientific basis for the technology is sound. There have been some publications that describe control of wax and hydrates with cold flow. Some DeepStar reports have raised questions about the feasibility of cold flow wax and about the economics of hydrate slurry pumping. Even with these questions, cold flow technology may make it possible to run long uninsulated tiebacks. There are still fundamental questions concerning slurry creation, thermodynamics, slurry properties and restart. These fundamental questions are addressed in the Phase II of this project.

Pigging

Pigging commonly refers to passing engineered solids through a pipeline in order to clean and/or inspect the pipeline. The status of pigging technology has been heavily reviewed in both the DeepStar and open literature. In particular, the need for development of reliable single trip pigging operations to eliminate the use of round-trip pigging and dual flow lines has been highlighted (DeepStar Report CTR 4303-1, 2000 and DeepStar Report CTR 6302, 2004) as essential for increasing the feasible lengths of subsea tie-backs. The amount and character of the solid deposits, which could result during cold flow, will likely affect these single-trip pigging operations; thus these effects must be quantified. In particular, the frequency and typical mission parameters of cold flow-single pigging has yet to be well identified. At least one cold flow seeding technology is relying on pigging technology to help create the cold flow slurry (DSV CTR 5201-3a, 2001), and this type/design of pig may or may not be the best type of pig to run in the longer subsea-tieback line itself.

A force balance for a scraper pig has been described in the literature as follows:

$$F_t = F_b + F_s + F_{ws}$$

Where,

F_t = Total Force to move the pig (static force for constant velocity, no acceleration).

F_b = Baseline force (frictional) between the pig and pipe wall

F_s = Breaking force of wax (gel strength?)

F_{ws} = Frictional force between wax plug and wax deposit

Ideally these forces should be quantified from field pigging data of cold flow demonstration/ pilot-scale tests for different flows (i.e., multiphase, export oil, etc.). From this type of data and other typical flow assurance evaluations, guidelines can be prepared for allowable pigging interval/frequency. Specific design of pigging methods for the generation of cold flow slurries such as the "Wax Eater" (DeepStar CTR 5201-3a, 2001) can be envisioned based upon identification of characteristics and trade-offs of various cold seeding methodologies for creating cold flow slurries.

Mechanical designs for pigging tools which incorporate the latest technological developments for dealing with traditional concerns such as multiple diameter lines, subsea launching, and flow bypass could be completed. Novel designs, such as employing "ice pigs" (Robins, 2003 and Shire et. al., 2005), can also be more effectively considered.

In summary, pigging is the mainstay of remediation technologies and would be considered a "must-use" technology for long-distance tiebacks. Option to pig the line as a backup must be available to ensure a robust cold flow system. However, the effectiveness of pigs in cold flow situations has not been tested extensively.

Internal Coatings

Internal coatings are used to prevent wax crystals and particles from precipitating onto the internal walls of pipelines. Common coatings are phenolics, epoxies, phenolic-epoxies, polyurethanes, nylon, and Teflon (Buck, 2006, DEEPSTAR DSIIA A906-1, Volume 1). In theory, the chemical nature of the coatings should work to prevent wax-surface molecular interaction; in experiments and field tests; however, physical parameters turn out to be more important in determining the effect of the coatings on deposition (Buck, 2006 and Efner, 1996, DEEPSTAR 3205-1). In addition, many tests have shown that the insulating nature of some of these coatings does more to prevent deposition than its chemical nature (Efner, 1996, DEEPSTAR 3205-2 and Hsu, 1997, DEEPSTAR 3205-3). Surface finishing for smoothness in an effort to reduce fluid-pipe friction has failed in every test to prevent deposition, and various studies have concluded that internal coatings do not prevent wax deposition (Efner, 1996, DEEPSTAR 3205-1).

One study in particular, however, has shown that nylon coatings seem to decrease wax deposition at high flow rates and temperatures close to the cloud-point temperature (Hsu, 1997). This may be of interest in cold flow technologies, but it will need to be determined if the deposition reduction holds for slurries below their pour point. Also, wax-hydrate interaction with nylon coatings has not been tested. All other coating technologies would be insufficient for cold flow systems.

Cost is a definite concern with application due to the large amount of needed specialty material, giving a rank of 3. There is an enormous range of possible failure, resulting in a rank of 1 (again, consideration should be given to nylon).

Chemical Inhibition

Properties of chemicals affecting pour point depression are described by Mankan and Ziegler (2001):

- The enhancement of interaction between the inhibitor polymers and waxes in oil is important.
- The polymer backbone has a slight effect on the pour point depression.
- The pendant chain carbon number has an optimum with respect to its effectiveness.
- The polymer molecular weight has no significant impact.
- Properties of solvents to keep the polymer in solution are also important.

The performance of wax inhibitors with different oils (Garcia et. al., 1998) is shown in Table 1. The performances of wax inhibitor polymers improve when they are used in synergy with the oil composition.

Table 1: Impact of oil composition on the effectiveness of the wax inhibitors.

Item	Effective	Ineffective
Normal / (cyclo + iso)	low	high
Quantity of C24+	Less than 32%	Higher than 52%
Wax distribution	Bimodal	Monomodal

Pedersen and Rønningsen (2003) showed the effect of wax crystal modifiers on WAT, pour point and viscosity. The chemicals used were polyalkyl methacrylate, a copolymer of ethylene and vinyl acetate (EVA), polymeric fatty ester, a copolymer of polyalkyl acrylate and vinyl pyridin, a mixture of EVA and copolymers of maleic acid anhydrate and α-olefin. Major viscosity reduction was observed in the temperature range of 10-25°C for all the cases of the chemical doping up to 1000 ppm. This result provides proof that the chemicals prevent the formation of wax network by interacting with waxes of the carbon number ranging from C21-C45.

The effect of chemical structure on pour point depression is tabulated in Table 2 as an example. The chemical doping of acrylate polymers results in significant reduction of pour point compared with the addition of ethylene vinyl acetate (Lindeman and Allenson, 2005).

Table 2: Performance of different classes of wax inhibitors. The tests were performed with 1000 ppm of additives in the same crude oil (the pour point of oil used was 18 ^oC without inhibitors).

Polymer	Ethylene vinyl acetate		Ester-type	
	ELVAX 150	ELVAX 240	Polyacrylate	Polynethacrylate
Molecular weight	87,767	82,900	97,730	103,900
Tm (^oC)	60-63	70-74	53	48
Degree of Crystalinity, %	-	-	50-55	20-26
Pour point (^oC)	10	4	-12	-15

The use of some low-dosage chemicals for prevention of hydrates and waxes is common, but little information is available in the open literature about the nature and mechanism of these chemicals.

Chemical inhibition alone would not be applicable to cold flow. Targeted chemical injection will be part of a total solution for wax/hydrate management and remediation. Even though general solutions can be structured for oils of wide-ranging compositions and for a variety of conditions, chemical injections are designed to address specific oils, conditions, and problems. The scientific basis on the mechanisms is available for some chemicals, but most knowledge concerning applicability is empirical. The upfront cost of developing a chemical solution can be high, and the associated remediation cost can be significant depending on the amount of chemical required and the application frequency.

Sonic Methods

Sonic management methods are not common. The concept is to position an ultrasonic generating device adjacent to production tubing to “disintegrate” wax formed at the walls (Towler et. al., 2007). Ultrasonic waves also increase the temperature of the flowing oil (in laboratory experiments).

A number of reports on wax detection methods are available. DeepStar (2A)A212_1 identifies methods of monitoring hydrates and solid paraffins in subsea flowlines, specifically to detect the presence, deposition, and buildup. In DeepStar 2A A906_1v2 a method of measuring wax deposition thicknesses is reported. In DeepStar 3208-2, it was determined that acoustic techniques for removing paraffin in pipes are not effective or practical.

Sonic methods have been tested at bench scales. The scientific basis for their effectiveness has not been established. It is not clear if these methods would work with hydrates and wax. As a result, this technology has been rated low in our evaluations for applicability, scientific basis and cost.

Biodegradation and other Methods

Even though bio-degradation has been a well-researched technology, i.e., for use in microbial recovery of waxy crude oils from oil reservoirs, limited emphasis has been placed on these methods for pipeline remediation. This may be due to the fact that microbial processes are typically slower than what might be required for fast(er) pipeline operations. Wax control by biocatalytic degradation of high-paraffinic crude was recently reported by Kotlar et. al. (2007). They isolated a strain of Acinetobacter and studied the degradation of long-chain alkanes. The applicability of the method under flowing conditions and in other environments need to be investigated.

Some other methods such as microwave detection and remediation methods were looked at in DeepStar and patent literature. None of these methods appear to be applicable to cold flow over long distances. Even with significant developments, these methods will have to address dispersion of agents and mixing in pipelines. At the current time, the technologies have neither been demonstrated, nor do they have a good scientific basis. As a result, these technologies have been rated low on all of our evaluation criteria.

Coiled Tubing and Active Heating

The coiled tubing technology is becoming more prevalent in solving flow-assurance problems (Quintero et. al., 2008). The technical applicability of the method is oftentimes limited by pipeline dimensions and geometry. The coiled tubing options along with pigging have been discussed in detail in DeepStar 6302, a summary of which is provided in the following section.

Dual insulated flow lines, is an industry standard for managing wax/hydrate problems. Single insulated buried lines (like the Macher tie-backs) are also seen. Chemicals are part of the flow assurance solution in these cases. For single insulated lines, subsea pig launchers are part of the design, although not very common. In some instances heated, dual flowline designs are used. One example of such design is the King field, where active heating is provided by circulating a glycol-water mixture.

In the Huldra-Veslefrikk pipeline field (hydrate in condensate production), a direct electrical heating (DEH) through electrical current was applied to generate heat through the steel pipeline wall. The electric power cable strapped to the thermally insulated pipeline (polypropylene coated super-martensitic steel, 13% Cr, 2% Mo) in a piggyback configuration. Fluid temperature generated by DEH was maintained at greater than the equilibrium temperature of hydration formation. The pipeline was eight inches (8") in diameter and ten miles long. Safety and reliability were issues due to aging or accidental shorts. This technology has seen limited application and is not recommended for long distance tie-backs (Urdahl et. al., 2004).

The applicability of active heating as a wax/hydrate management technology is well established. The question is implementation over long distances and cost. In terms of scientific basis and applicability these technologies are ranked high on our list, but the cost is likely to be prohibitive.

Summary of Findings from DeepStar 6302

Kellogg, Brown & Root performed a comprehensive evaluation of 15 benchmark and wax-mitigation technologies and developed comprehensive rankings for the technologies evaluated. All of the technologies considered wax mitigation and did not specifically address hydrates. The benchmark technologies and assigned ranking (with the lowest being most preferable) are summarized below, followed by the mitigation technologies.

- Single insulated pipe (1)

The pipeline is designed with insulation so that flow remains above the wax appearance temperature along the entire length of the line during steady state flow. Ideally the temperature will be above the wax appearance temperature so that precipitation and deposition does not occur.

- Dual flowline – roundtrip pig (3)

Dual flowlines are another standard option that allow introduction of pigs from the surface facility. Wax-removal pigs can be pushed out one line and then flowed back the other with wells shut in.

- Single pipe – wax in place (7)

An oversized pipe is designed for anticipated wax build-up during its design life, and wax is allowed to deposit.

- Single flowline – heat (9)

The flowline is heated as necessary to prevent wax deposition. This method would generally be combined with some insulation.

- Single flowline – chemical treat (11)

Chemicals are injected into the line at the well end to ensure that wax deposition does not occur in the line.

The mitigation technologies examined in this study with ranks are listed below.

- Crawler pig (2)

Upstream crawling pig powered by flow through annular turbines in the pig body. The pig carries rotating cutter blades on the nose to remove wax. It can also be configured to return with flow as a conventional pig.

- Coiled Thrust and Carry (TAC) pig (4)

Coiled tubing with a pig mounted on the end. The tubing is pulled through the flowline by the pig.

- SGN (Nitrogen Generation System) (5)

A coiled tubing apparatus that allows the introduction of hydrochloric acid and ammonia. The two chemicals mix to produce heat and nitrogen.

- Go-Flo (6)

A combination of chemical, mechanical, and thermal treatments can be applied using the apparatus to clear blockages. A coiled tubing apparatus that uses composite tubing to reduce friction and a crawler to tow the coiled tubing through the line.

- Subsea pig launcher (8)

Single flowline with a Subsea Pig Launcher (SPL) operating wax removal pigs. Valve systems would be used to moderate the pig motion in multiphase flow.

- Jetstream pig (10)

A pig with combination heat generation using slugs of hydrochloric acid and ammonia.

- Power pig (12)

An SPL launched pig with a jet cleaning head to remove wax. The pig employs active braking to control motion and reduce the pig velocity below the flow velocity as it moves downstream.

- Auxiliary line (13)

With flow shut in, a cleaning pig is driven out the flowline while returns flow through the auxiliary line.

- Progressive pigs (14)

A sequence of increasingly aggressive pigs is launched on-stream from an SPL to clean the line.

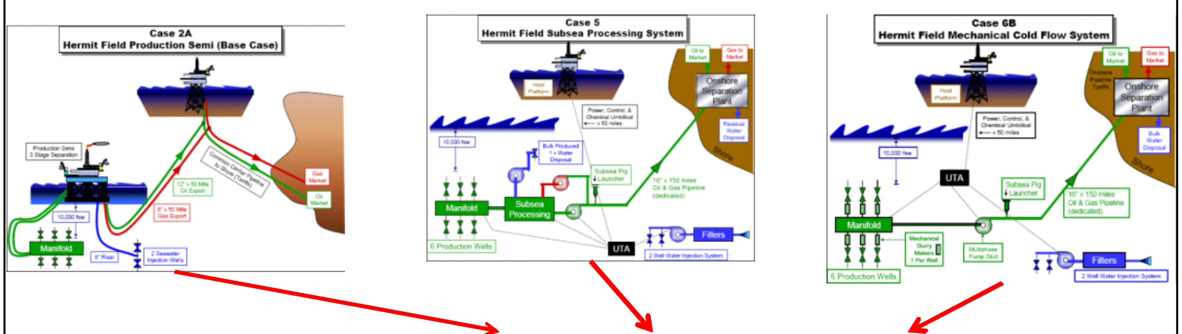
- Wax eater (cold flow) (15)

At the inlet to the flowline, a looped section of pipe with a continually circulating pig cools the fluid and precipitates the wax. The pig scrapes the wax from the wall of the pipe, and the wax then flows in suspension through the pipeline.

The major finding in this study was that none of the mitigation technologies were as reliable or robust as the benchmark, single insulated line option. The most promising technology to run a single uninsulated line over long distances was identified to be the "crawler pig." The cold flow "wax-eater" technology received the lowest (most unfavorable) rank, primarily due to the assumption that the technology will not work in the presence of hydrates, and that hydrate mitigation chemicals would be required.

Summary of Economics of Cold Flow from DeepStar 7901-8

This DeepStar report offers some insight concerning cold flow economics if slurry transport were to be adapted. After comparing produce-to-beach scenarios, this report concludes that using cold-slurry technology and multiphase pumps provide a robust facility solution. This solution does not deliver the projected performance of the more technically challenging Subsea Processing scenario or the Internal Rate of Return of the Base Case, the latter which was the conventional dual line to the platform and export lines to the beach. One of the primary reasons for this conclusion was that the cold flow technology with slurry transport would take longer to produce the same volume. The different scenarios considered and the basic economic parameters are compared in Figure 4.



	Base Case	Produce to Beach		
	Case 2A	Case 5	Case 6A	Case 6B
Table 1-1 Economic Comparison	Semi w/ Manifold & Surface Processing	Subsea Processing for Bulk Water Sep.	Chemical Slurry Multiphase Pumps	Mechanical Slurry Multiphase Pumps
Total CAPEX ($ Million)	793.01	893.46	928.64	935.60
Total OPEX ($ Million)	521.60	200.23	297.37	279.81
Net Present Value ($ Million)@11%	**454.38**	**726.68**	**578.52**	**584.87**
IRR:	35.94%	36.86%	30.79%	30.90%
Million BOE Produced	134.672	134.461	134.915	134.915
CAPEX/BOE PRODUCED	$ 5.89	$ 6.64	$ 6.87	$ 6.92
LIFTING COST (OPEX/BOE)	$ 3.37	$ 1.48	$ 2.20	$ 2.07
Total	$ 9.26	$ 8.12	$ 9.07	$ 9.00

Figure 4: The scenarios considered in DeepStar 7901-8 for production-to-beach alternatives and the basic economic parameters.

Ranking Criteria (1 - 10 on each)

Is the technology as defined, applicable to cold flow conditions?

1. What is the scientific basis of the proposed method?
2. How easy/difficult would it be to deploy the method over several hundred miles of pipe?
3. Under what conditions is the method likely to fail? (range of applicability)
4. What are preliminary cost estimates?

Based on these criteria, the following are our rankings of the technologies evaluated. Highest rank would indicate preferred technology. Please note that the ranking scale (1 - 10) is different from that used in DeepStar rankings and the order is reversed as well.

Table 3: Technology evaluation using the ranking criteria provided in the proposal guidelines.

Technology	Cold Flow Applicability	Scientific Basis	Implementation over several hundred miles	Range of Applicability	Cost	Overall Rank
Cold Seeding	9	8	7	5	7	7.2
Pigging	10	10	9	10	5	8.8
Coiled Tubing	7	9	3	8	7	6.8
Active Heating	9	10	5	7	3	6.8
Chemical Inhibition	5	6	5	5	5	5.2
Internal Coatings	3	2	9	1	3	3.6
Sonic Methods	1	2	7	1	3	2.8
Magnetic Methods	1	3	1	1	3	1.8
Microwave Methods	3	3	1	1	1	1.8
Biodegradation	2	1	1	1	5	2

The Experimental Program

Wax and hydrate control methods which could allow use of longer (over 10 miles total length) uninsulated tie-backs or export lines, without requirements for parallel flowlines and round trip pigging potentially offer significant reductions in CAPEX for future deepwater production strategies. However, fundamental concepts and hypotheses need better quantification and demonstration to validate their actual performance in the field. The literature review has determined that there was preliminary evidence that cold flow was effective in controlling both the wax and hydrate deposition. The fundamental concept of cold flow under different flow conditions must first be proven, however. The hydrate experiments would require high-pressure conditions with a significantly higher number of experimental parameters. The industrial steering committee advised us to focus on issues related to wax control using cold flow based on the time and budget available for the project.

The first question was the samples and oils which would be available for the study. Use of models of oils would allow for better control of the experiments and perhaps better reproducibility. The wax appearance temperatures and pour points of the Gulf of Mexico (GOM) crude oils are separated by tens of degrees with low pour points. The wide carbon number range in a crude oil is also not easily reproducible in model oils. Hence the first task in the research program was to constitute the right kind of models oils – oils with a reasonable spread between the WAT and pour point and oils with the approximately similar flow properties (viscosity) as the GOM crude oils. The second task was to evaluate the feasibility of "cold flow" under various thermal flux and solids-loading conditions. In creating the slurry in cold flow, the heat exchanger unit and the mode of heat transfer would be important in controlling the nature of wax particles. Hence, one of the tasks was the design and construction of the heat exchanger needed to create the slurry. The idea was that the testing of such equipment may lead to the design of a larger commercial-scale unit. The steering committee also wanted us to examine restart implications during the cold flow process. It was important to study how restart pressures on shutdown in cold flow compare to the restart pressures under "normal" shutdown conditions.

Experimental System – Design and Fabrication

The experimental plan was to determine the feasibility of "cold flow" application in deep sea pipelines as an effective measure against shutdown due to deposition plugging. To do this, we worked to find a way to accurately determine existence of deposits. With knowledge in a laboratory-scale system of deposition mechanics and "cold flow" behavior in both slurry and non-slurry conditions, we would be able to develop a good idea of the behavior in an actual pipeline with a live oil and thus determine whether or not "cold flow" can be a viable alternative to common deposition prevention and remediation practices.

The system chosen is a recycled flow loop, ½" in diameter to reduce flow requirements, with a controlled-temperature reservoir. The most important section of the flow loop is the exchanger section; this section is a pipe-in-pipe heat exchanger operating at counter-current flow, fitted with thermocouples and pressure transducers to give a thermal and pressure profile across the exchanger. The setup runs the coolant through the annulus and the oil through the center tub, creating an ideal temperature control system in which the inner fluid is only affected by the coolant and not ambient conditions while inside the exchanger. The rest of the flow system is exposed to ambient an condition (which, in most cases, is warmer than the oil, thus preventing deposition of wax in the main line). The pump is a very-low-shear gear pump operating up to but not limited to 3 gpm, and the reservoir is maintained using insulation, a copper cooling coil, and an external control system utilized in maintaining a constant experimental-section inlet temperature. Ethylene glycol is the coolant. All transducers are high-quality, high accuracy, flush-mounted Kulite 0 - 25 psig transducers, and all thermocouples are J-type Omega with a +/- 1°C accuracy. The external controller uses an RTD (resistance temperature detectors) with a high accuracy, and the reservoir temperature is compensated to maintain this RTD output. The process and instrumentation diagram (P&ID) of the loop is shown in Figure 5. Figure 6 shows the schematic of the flow loop.

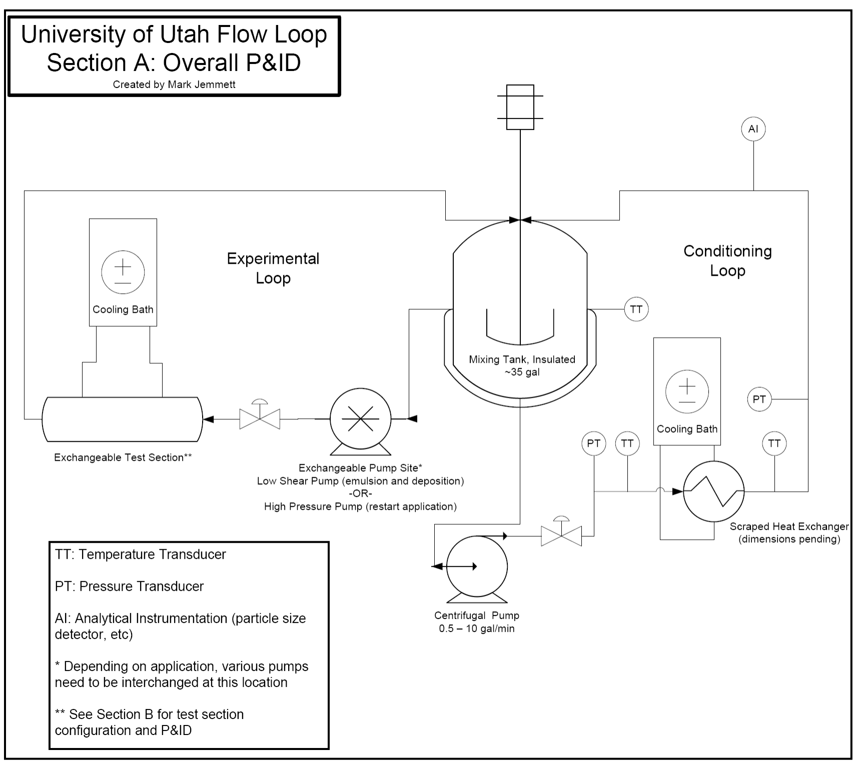


Figure 5: Process and instrumentation diagram (P&ID) of the University of Utah flow loop for cold flow testing.

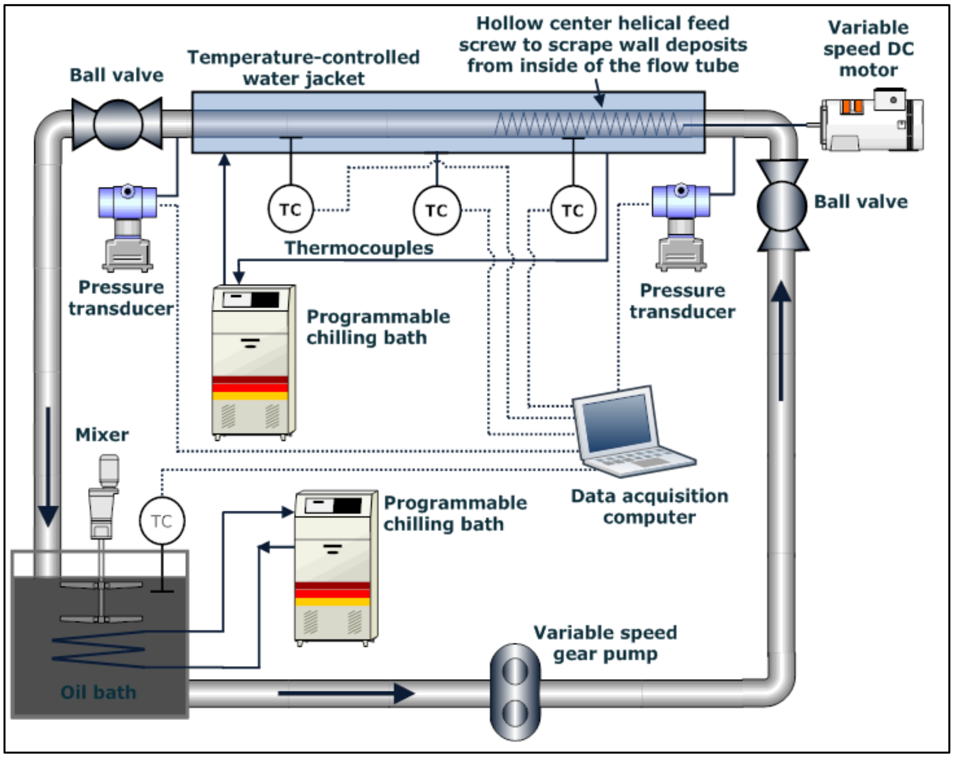


Figure 6: Schematic of the flow loop used in studying cold flow.

Two types of exchangers have been manufactured. The first is a stainless steel section, 4 feet in length; the second is a clear acrylic exchanger that allows for flow visualization, particle image velocimetry (PIV), and visually confirmed deposition presence. A photograph of this loop is shown in Figure 7.

To control factors that could lead to deposition, additional systems are incorporated. To measure particle size distribution of wax particles and water droplets (if present), Canty Vision visualization equipment is used. With this aspect of the flow known, particle size can be adjusted by controlling cooling temperature and mixing/shear rates applied in the reservoir. A second control system related to particle-size control is the scraped heat exchanger, which was designed and built.

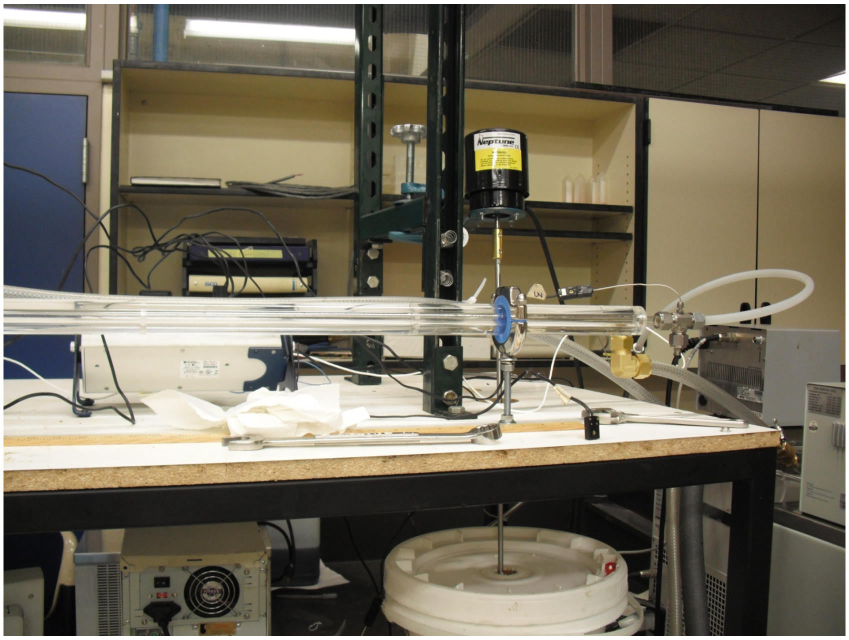


Figure 7: Photograph of the flow loop used in testing the feasibility of cold flow.

This system is ideal for flow studies, particularly when coupled with deposition studies. One problem in most studies is that deposition presence is typically only determined using pressure drop data; this can lead to errors since any slight change in fluid temperature will affect the pressure drop across any test section, and if not interpreted properly can lead to false results. With visual confirmation of deposition presence, the pressure drop data can be confirmed or rejected. Furthermore, during slurry flow the larger particles settle and deposit on the lower half of the tube, allowing for PIV visualization of the gradually-constricting flow, allowing for even more accurate estimations of deposition thickness, deposition rate, etc. The visual element of these studies was valuable in understanding what happens during deposition in “cold flow”.

The Model Oil

The model oil used had the following characteristics.

- 92.5% white mineral oil
- 6.0% LVGO Wax (Light Vacuum Gas Oil Wax)
- Higher distribution than normal paraffinic wax
- 1.5% Normal Paraffinic Wax

- WAT 25^0-22^oC
- Pour point: 7^oC

The carbon number distributions in the two waxes used in the model oil are shown in Figure 8, along with the log-normal distributions. Most crude oils exhibit a linear log-normal curve. The model oil wax distribution deviates from the linear at low carbon numbers but follows a near linear profile at high carbon numbers. A number of important oil properties are determined by the concentrations of higher molecular weight paraffin waxes, and the model oil was expected to possess the required characteristics. The WAT of the oil was measured to be between 22^oC and 25^oC by using a variety of techniques (viscometry and Fourier Transform Infrared (FTIR) Spectroscopy). The pour point was about 7^oC. The 18^oC difference between WAT and pour point (similar to normal crudes), allows for larger range of testing.

The density and the viscosity values of the model oil are shown in Figure 9. The density is linear with temperature while the viscosity plot shows that the model oil is non-Newtonian at around 13^oC. The viscous and the elastic moduli of the model oil are shown in Figure 10. The temperature point at which they turn over (7^oC) is interpreted to be the pour point of this mixture model oil.

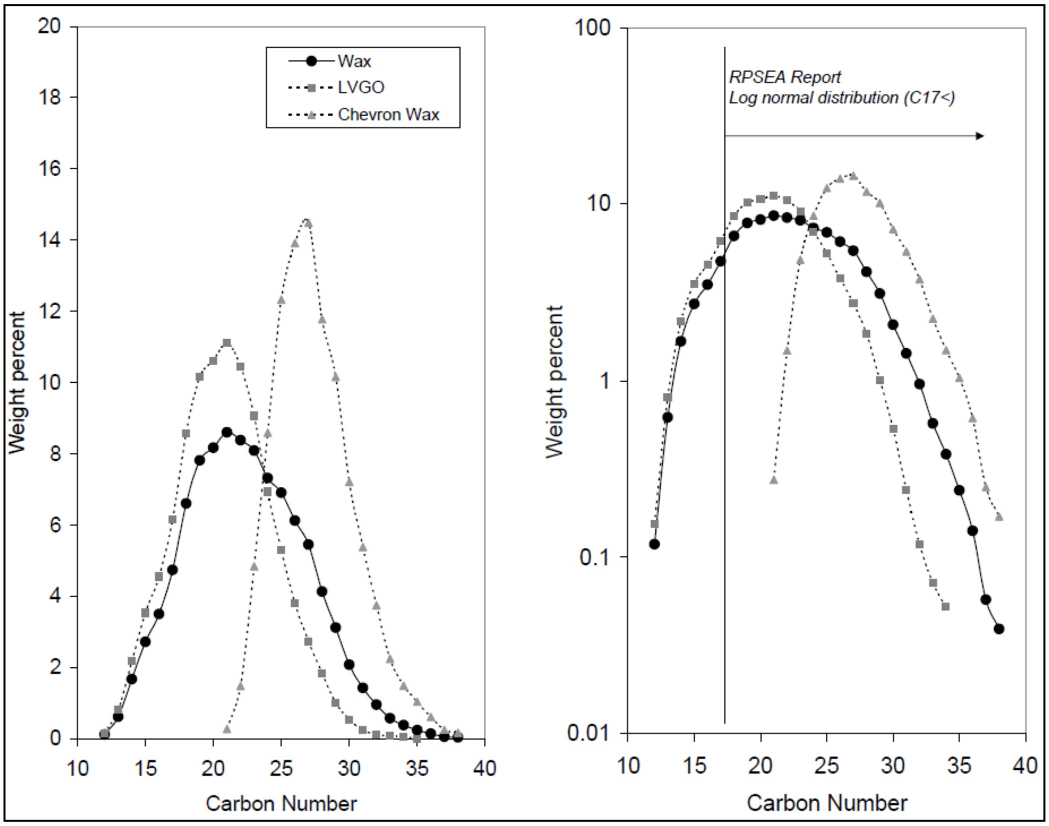


Figure 8: Compositions of the waxes and of the mixture used in the model oil.

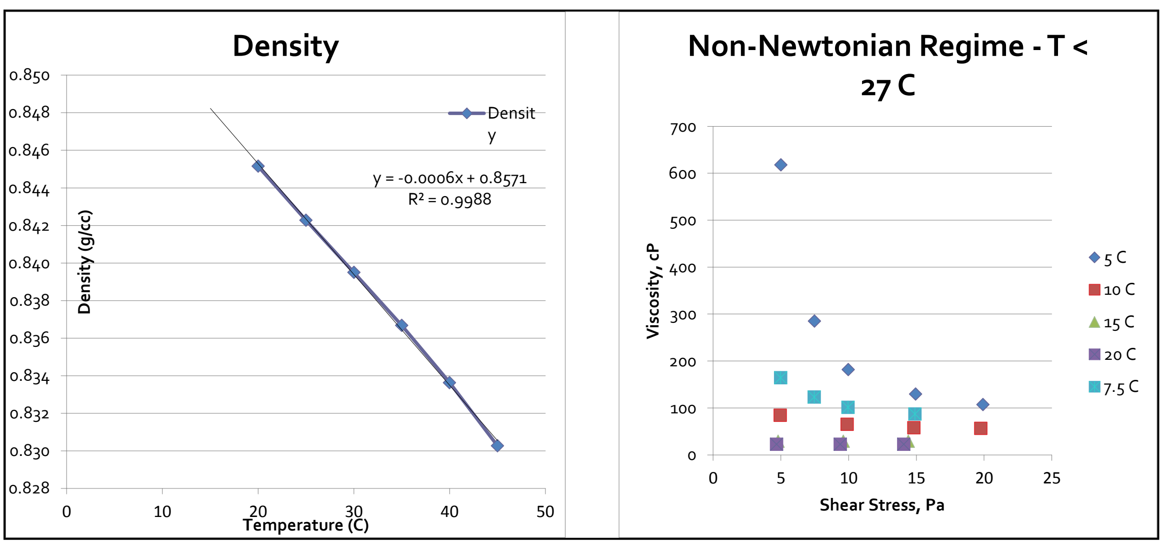


Figure 9: Densities and viscosities of the model oil that is being used in the cold flow investigations.

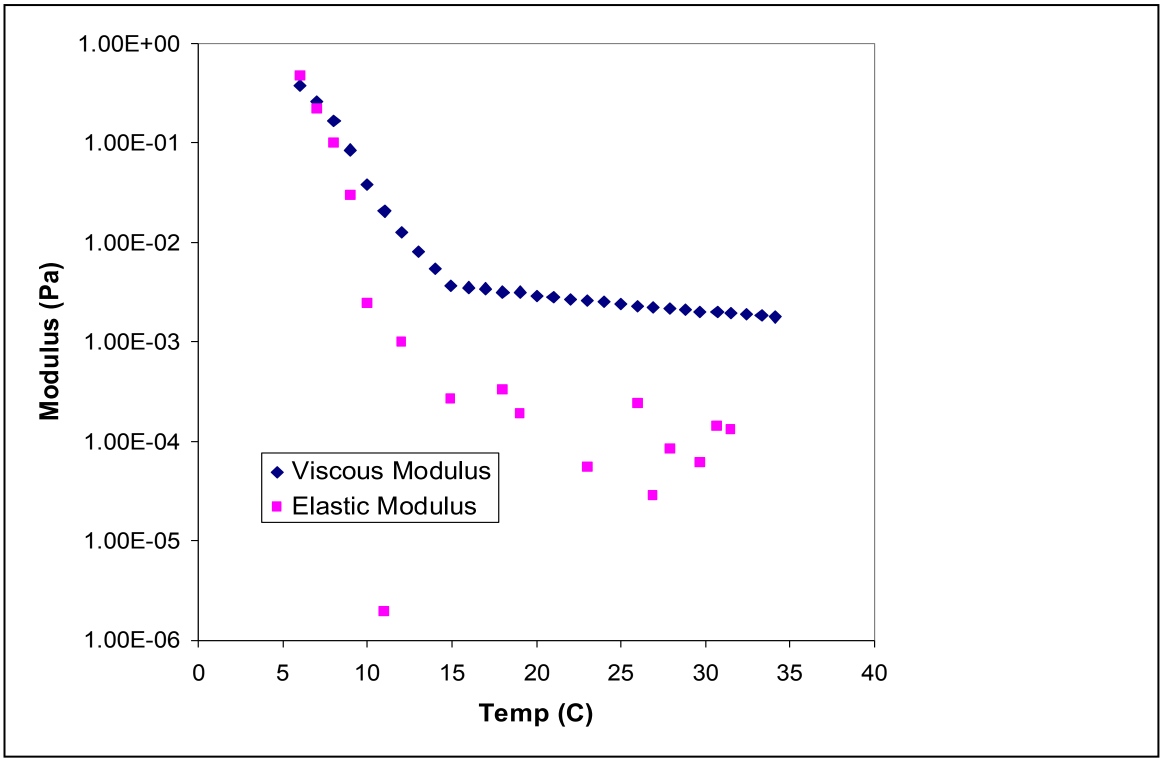


Figure 10: The viscous and the elastic moduli of the model oil. The temperature at which they turn over (7°C), is interpreted to be the pour point of this mixture model oil.

Cold Flow Experimental Results

Experiments were run using both the stainless and acrylic test sections using a variety of flow rates, covering the laminar, transition, and low turbulent regimes. With the stainless loop, pressure drop was the only method of determining deposition presence. With the acrylic loop, pressure drop, PIV, and visual confirmation were all used. Additionally, use of PIV with the acrylic loop confirmed that careful use of pressure drop while maintaining constant temperature and flow rate provides accurate deposition thickness calculations.

For the stainless experiments, pressure drop across the test section increases steadily with deposition over time. This increase continues until reservoir wax content diminishes with long-term (ten day plus) tests. Pressure increases at the head of the test section while remaining steady at the downstream transducer; this indicates both a Hagen-Poiseuille type of pressure drop with deposition, in addition to an effective constriction-induced pressure drop. Both are needed to correctly fit the pressure drop data to deposition thickness.

Figure 11 shows the result of one typical "hot flow" test in the stainless loop. The experiments were performed with an ambient temperature of 16°C and a test-section temperature of 12°C. There is a steady increase in pressure drop. The pressure drop can be used in calculating the thickness of the deposit (Figure 12). Several experiments were performed. In the stainless experiments, lower flow rates in the laminar and early transition flow regimes slow deposition onset, but once deposition sticks, the wax deposits grow more quickly than in higher flow-rate tests.

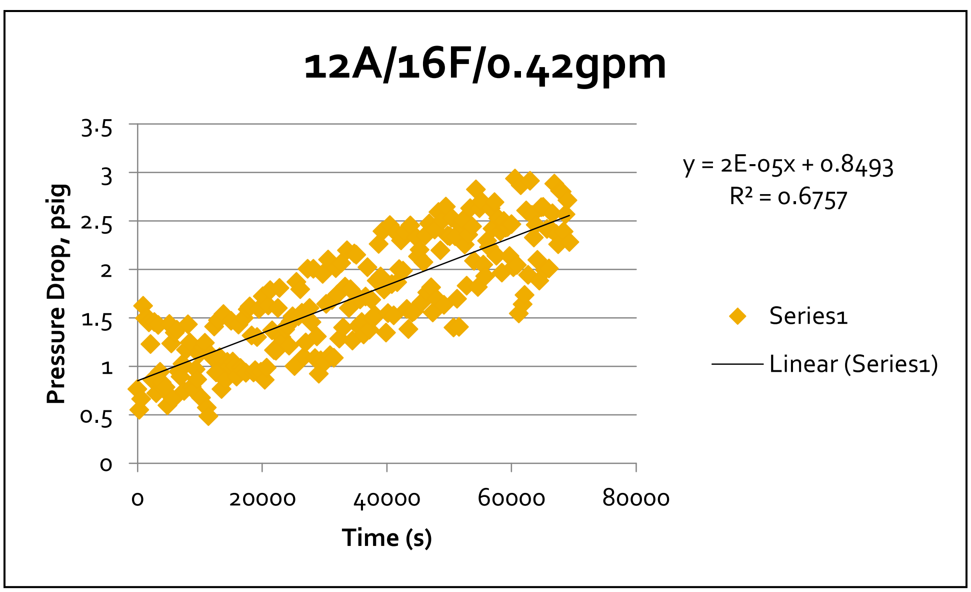


Figure 11: Typical "hot flow" results where there is thermal flux between the ambient and test section. The ambient is at 16°C, the test section is at 12°C, and the flow rate is 0.42 gallons per minute (gpm).

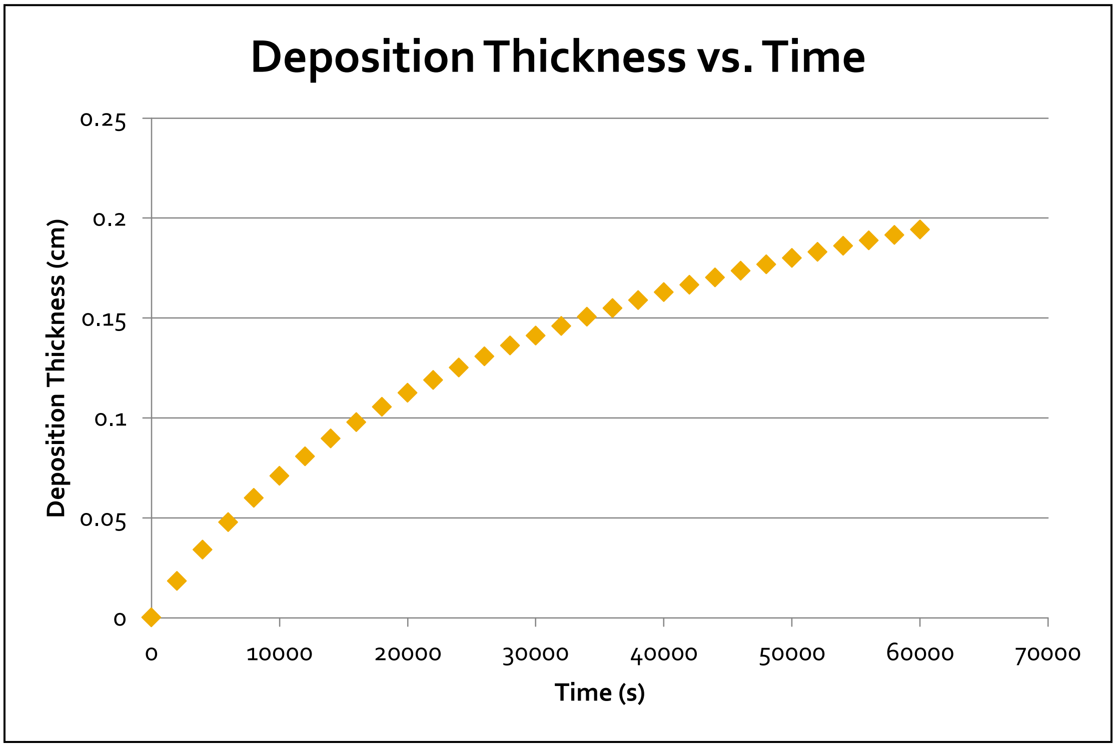


Figure 12: Deposit thickness calculated using the pressure-drop data in Figure 11.

Stainless "Cold Flow" tests showed no increase in pressure drop whatsoever, indicating no deposition over the 24-hour test periods. A typical cold flow result is shown in Figure 13. This was expected; however, it was also noted that slight differences between the oil and coolant (0.5 to 1°C, with the coolant lower in temperature) showed no deposition either, regardless of slurry conditions. This agrees with "gel sloughing" but appeared to be true even in very low flow conditions (less than 4 Pa wall shear) in the acrylic tests, indicating a possible thermal aspect in addition to mechanical stresses to gel stability under flux conditions.

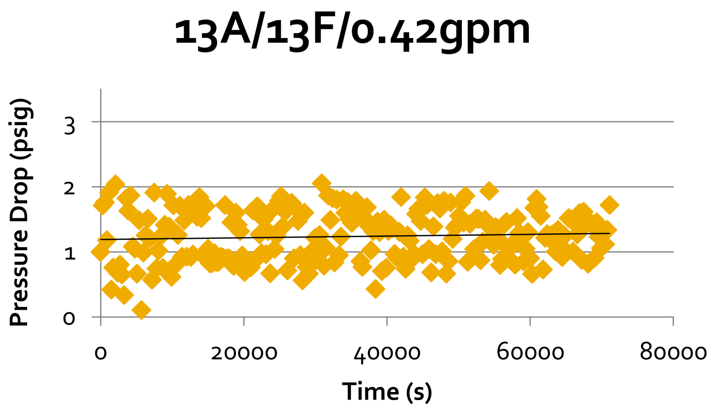


Figure 13: Typical "cold flow" results in the stainless steel flow loop. The temperatures of the ambient and the test sections were held at 13°C, while the flow rate was 0.42 gpm.

The pressure fluctuations are significant in Figure 13. Pressure reading accuracy was *significantly* improved with the presence of a flow dampener (empty straight section in-line with flow, forcing oil flow in a 90-degree direction against the compressible air). The results of improved pressure readings are shown in Figure 14.

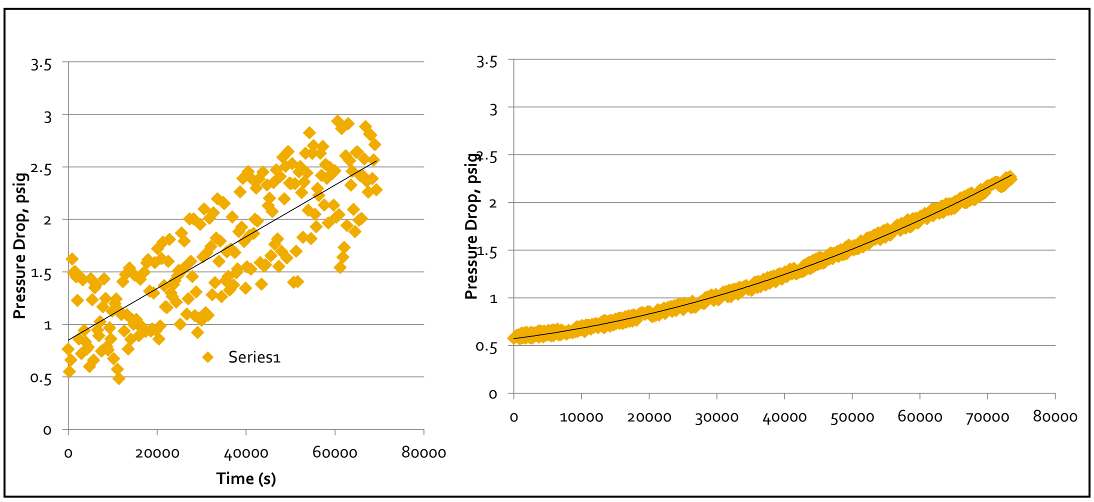


Figure 14: Pressure drop without the pressure dampener (left) and with the dampener (right).

Acrylic section tests showed interesting results; slurry flow conditions subjected to a slightly positive heat flux showed that deposition occurred first at the bottom half of the tube and then gradually climbed upwards over half a day (Figure 15). This was confirmed visually and using PIV (Figure 16). The deposition thicknesses calculated using the different methods is shown in Figure 17. For these experiments, the ambient temperature was 17°C, the test section temperature was 10°C, and the flow rate was 0.7 gpm. Non-slurry flow conditions exhibited fairly uniform deposition across the entire inner surface shortly (within minutes) after deposition begins under all flow regimes.

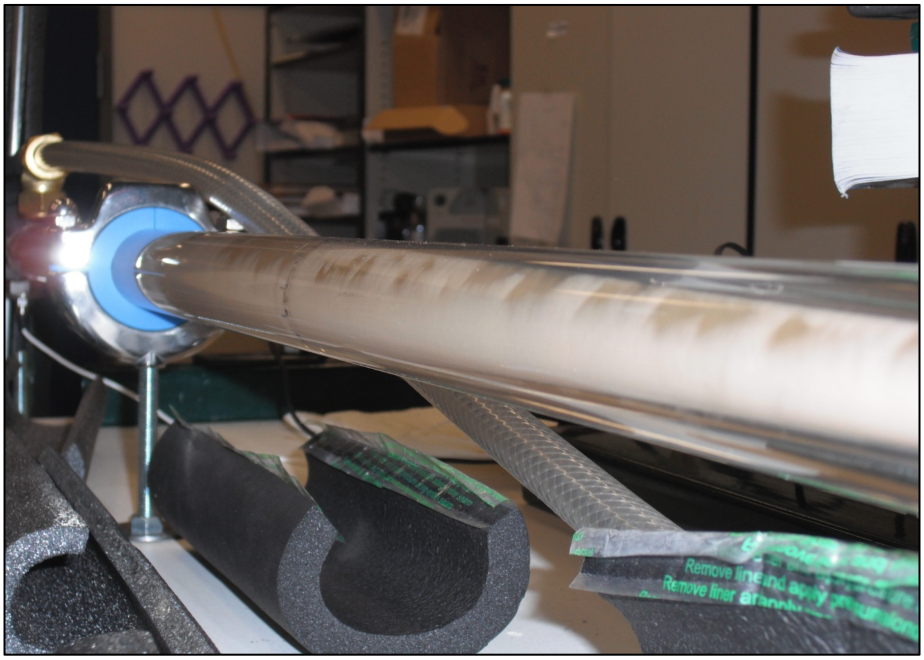


Figure 15: Uneven deposition observed in the clear test section.

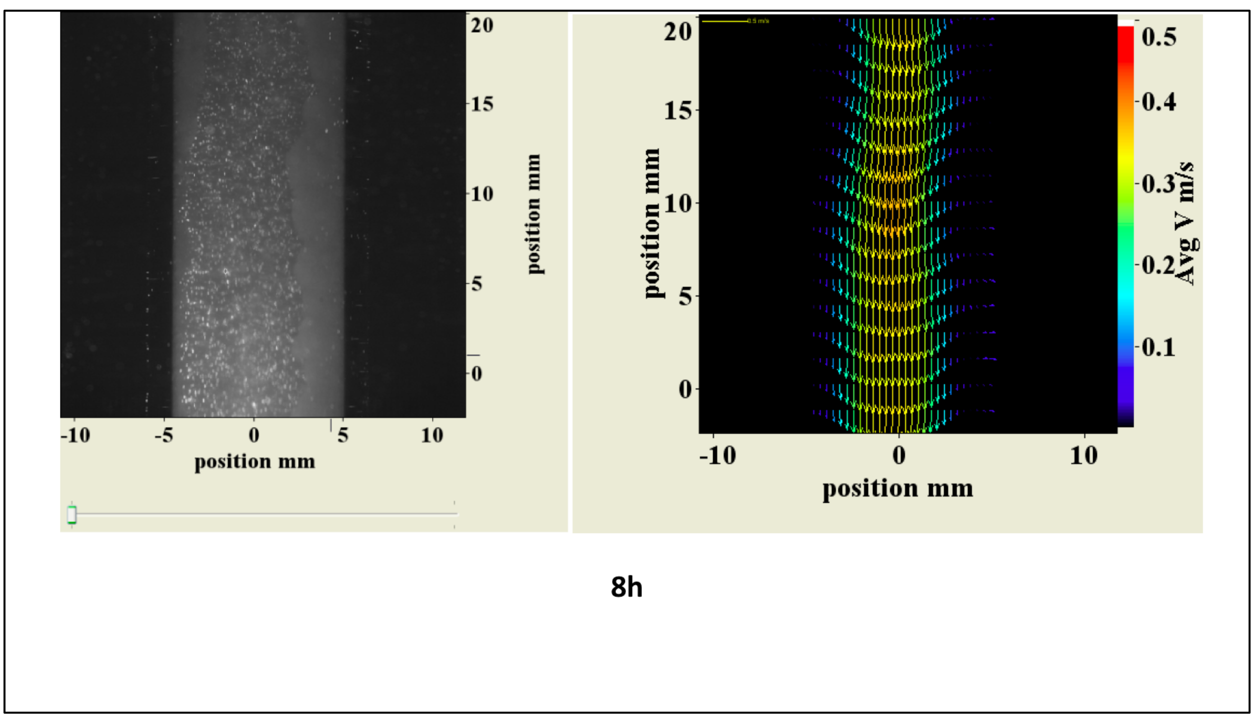


Figure 16: Non-uniform deposition confirmed using PIV. The velocity profiles are consistent with the deposition pattern.

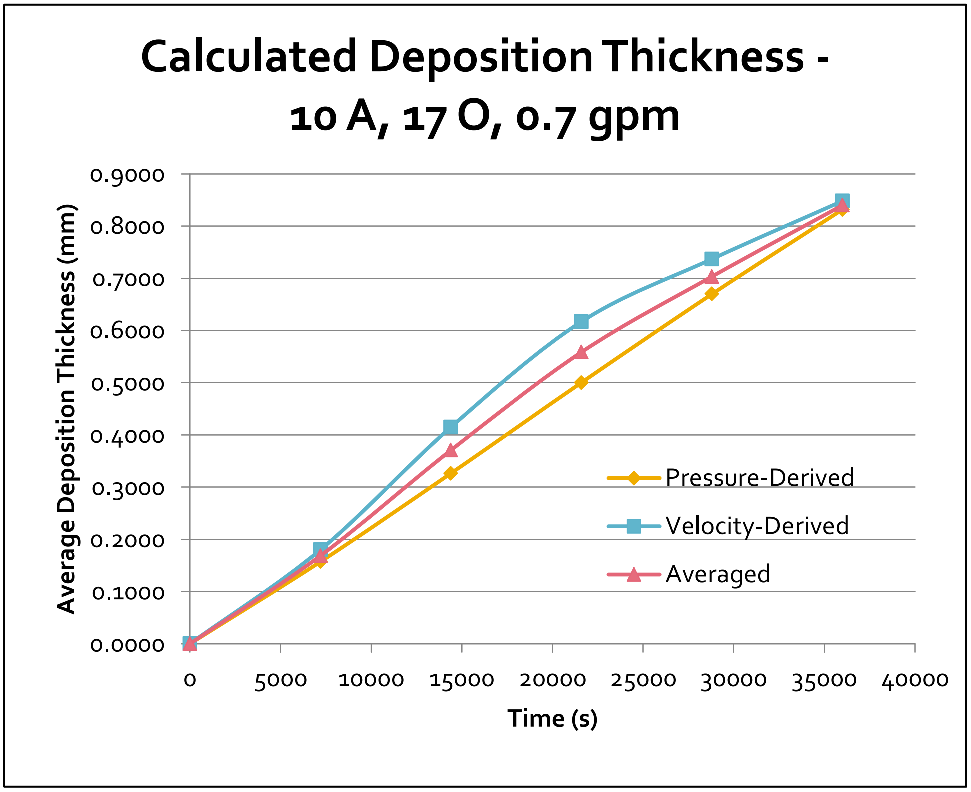


Figure 17: Deposition thickness calculated using different approaches for slurry flow experiments where there was thermal flux (10°C test section, 17°C ambient and 0.7 gpm flow rate).

Acrylic "Cold Flow" tests showed no deposition, even under "nearly Cold Flow" conditions as described earlier. This near isothermal condition was predicted by commercial pipeline software to exhibit deposition under the temperatures chosen (above pour point, below wax appearance), but a 10-day test at a high flow rate (early turbulent/transition regime) showed no deposition whatsoever.

Finally, as thermal flux was decreased by regulating the coolant temperatures, deposition rate was reduced until the "Nearly Cold Flow" condition where deposition ceased (about a 1°C differential). Please see Figure 18. This coincides with the results of previous studies, though in greater depth. Typical short and long terms test results are shown in Figure 19. The conclusion, therefore, is that "Cold Flow" conditions are successful in eliminating deposition during long-term flow tests, and this conclusion is backed up using pressure drop data, visual confirmation, and laser PIV. More importantly, however, is the suggestion from the data that isothermal conditions are not required for deposition to be eliminated. This was further investigated in the next section.

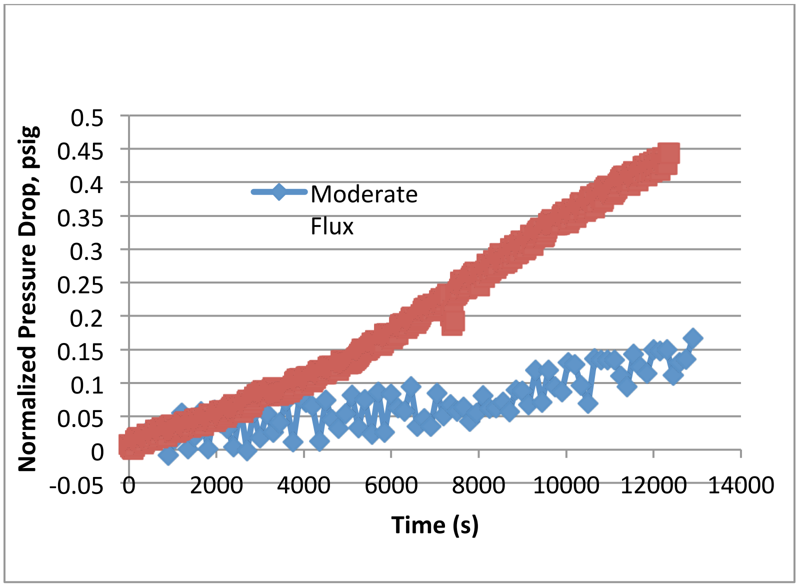


Figure 18: Reduction in deposition rate with reduced heat flux when identical flow rates were used.

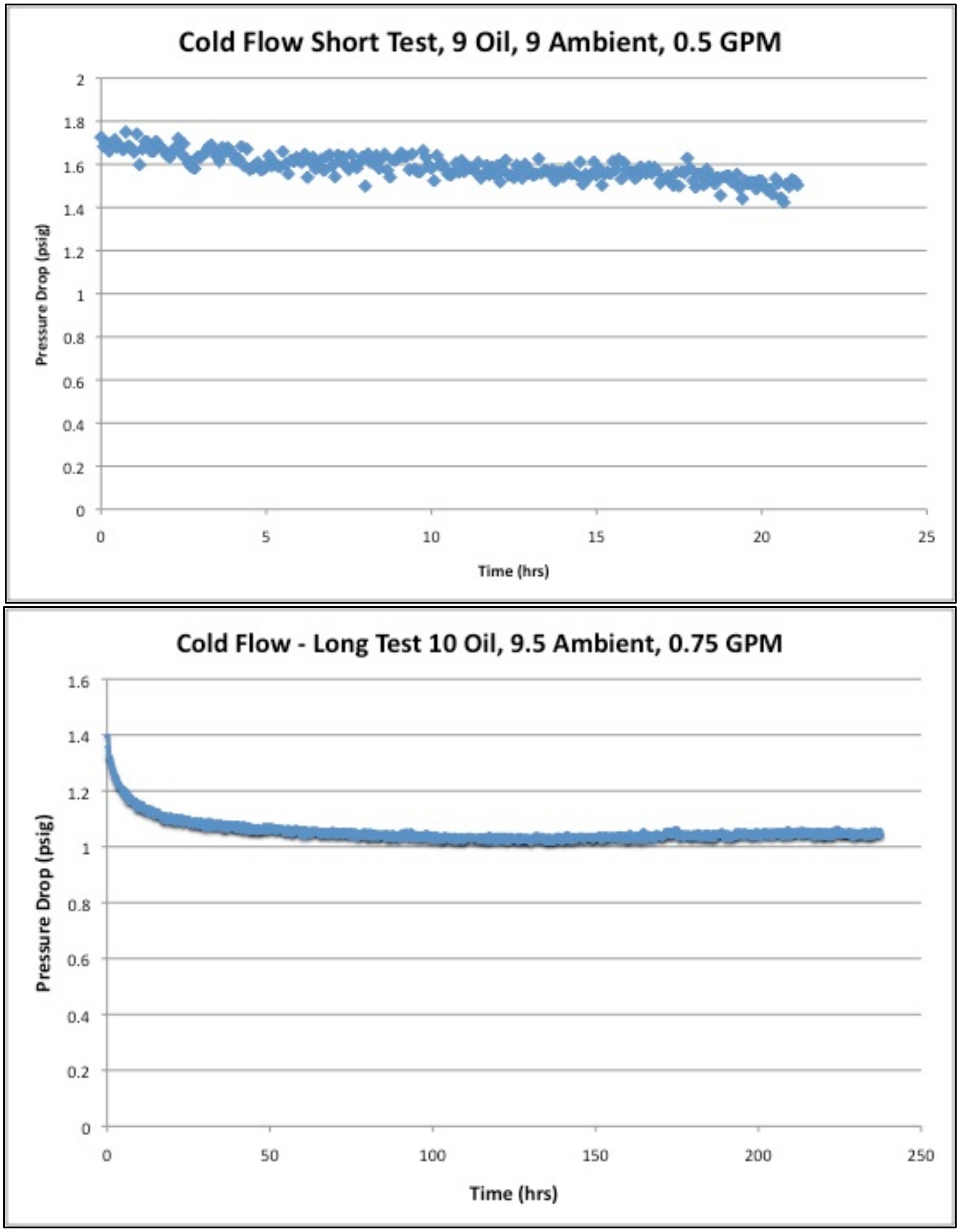


Figure 19: Typical test results cold flow – short term and long term. The tests showed no indication of deposition.

Cloud-Point Depression Study

Temperature management of the oil and cooling apparatus is critical in obtaining good, reliable data (Merino-Garcia and Correra, 2008; Bidmus and Mehrotra, 2009). In the case of "Cold Flow", isothermal conditions between the slurry oil and a cold section of pipe are needed; however, several studies have found that isothermal conditions are in fact not needed, although the reason for the multiple-degree discrepancy was not documented to be fully understood. This study seeks to explain, at least in part, a potential reason for this discrepancy in terms of how the oil itself is cooled and conditioned. A clear model oil containing 5 percent normal paraffin wax and 1.5 percent LVGO was conditioned in a well-mixed, insulated reservoir and cooled using an internal cooling coil. In practice, the fluid in the coil must be colder than the oil target temperature to reach said target in a timely and cost effective manner. The theory is that warm oil in the reservoir, when subjected to the sub cooled surface of the coil, experiences precipitation of waxes beyond that which is expected. Due to chemistry, surface area, and energy of crystallization, a hysteresis in precipitation and dissolving temperatures exists, thus preventing these waxes from readily going back into solution. In this study, sampling is direct from the reservoir at various conditions, and wax crystals are removed using paper filtration under vacuum-pressure (-10 psig) conditions to prevent inadvertent solubility changes within the solid-liquid slurry mixture. The filtrate is then tested for initial cloud point using FTIR and compared to the target oil temperature. The observed effect is a reduced filtrate cloud point between the target bulk temperature and coil temperature. This qualitative study suggests that due to this reduction in filtrate cloud point temperature, the temperature at which new precipitation and deposition will occur in a flowing system is reduced below what is expected. In fact, the simple act of cooling is distorting "Cold Flow" and other slurry flow results by reducing the component cloud point temperature of the oil.

Paraffins, large carbon chains and structures present within petroleum crudes, are a substantial source of lost revenue for the petroleum industry. They have the tendency to build as deposits on pipeline walls. These deposits reduce flow cross-sectional area, thereby reducing throughput and increasing the required pump duty necessary to maintain flow. Furthermore, in the case of pipeline shut down for maintenance, these paraffins crystallize under cooling conditions (such as hot oil subjected to cold subsea conditions) and can form cross-linked gels. These gels can stretch dozens of miles and require significant pumping pressure to restart in many cases; if the gel cannot be broken due to pipeline pressure limitations, the line must be abandoned or replaced at the cost of many millions of dollars.

Many methods of paraffin or wax deposition prevention and remediation have been explored over the years (Becker 2000; Bosch 1992; Sarmento et. al., 2004; Newberry et. al., 1986; Braden 1997; Ghedamu et. al., 1997) ranging from pigging, chemical additives, heat tracing, coatings, biological measures, magnetics, and acoustics. While only pigging, chemical additives, and line heating have shown any real promise in the field and are unlikely to be completely replaced, these methods can be cumbersome and expensive, particularly in wells that are in difficult, extreme locations. What's more, the general attitude worldwide is that petroleum reserves in the future are only going to get more and more difficult to produce in regards to location and composition (Swain 1995; U.S. DOE 2006), whether the latter includes asphaltenes, waxes, hydrate potential, acidity, or all issues combined.

In the instance of paraffin or wax, a relatively new concept called "Cold Flow" has emerged as a means of minimizing or preventing paraffin deposition by eliminating the heat flux in an uninsulated pipeline (Merino-Garcia and Correra, 2008). This is accomplished by reducing the temperature of the oil to that of the surroundings. For a crude oil with an initial wax appearance temperature above ambient conditions, this requires that the state of the flowing oil be solid-liquid slurry with the solids being precipitated paraffin crystals. Multiple studies have shown that, while increasing pump duty due to raised viscosity, this "Cold Flow" method indefinitely prevents and eliminates deposition by pulling paraffin out of solution, thereby eliminating its potential for nucleation and deposition on the walls, as well as eliminating the heat flux through the walls that introduces the deposition potential to begin with (Majeed et. al., 1990; Svendson, 1993; Kok and Saracoglu, 2000; Creek et. al., 1999; Singh et. al., 2000, 2001a, 2001b; Ramirez-Jaramillo et. al., 2004). Furthermore, evidence in rheometric systems has shown that gels formed from slurry initial states are significantly weaker than gels formed from "clean", pure-liquid oil states (Venkatesan, 2004; Magda et. al., 2009), giving "Cold Flow" one more benefit with future potential industrial application.

With the most recent studies, a curious artifact was discovered with regards to the temperatures at which "Cold Flow" successfully functions. Carefully controlled laboratory flow systems have shown that, while the oil's state is that of a slurry, ambient temperatures can actually be reduced a few degrees below that of the oil, effectively introducing a small but definitely existent heat flux across the wall. Theory and commercially-available models dictate that if a flux is present and if wax is available to deposit, barring mechanical shearing it eventually will form (Patton and Casad, 1970; Bott and Gudmundson, 1977; Jennings and Weispfessing, 2005; Wu et. al., 2002; Bidmus and Mehrotra, 2004; Parthasarathy and Mehrotra, 2005; Mehrotra and Bhat, 2007; Fong and Mehrotra, 2007). However, in all cases and tests with this ambient temperature reduction there was no such deposition. In the most recent study, using a clear heat exchanger wherein deposition could be visually seen and measured, this result was confirmed: there occurred no deposition out of a slurry with ambient temperatures being as much as 2°C below the bulk oil temperature. Bidmus and Mehrotra, (2009) came to a conclusion that part of the deposition elimination was due to the inner wall temperature being elevated above that of the coolant fluid, but, as explained by the authors of that study, this is insufficient to explain the total loss of deposition and apparent reduction in actual wax appearance temperature (WAT; also known as cloud point), or the temperature at which deposition can occur. The reason for the existence of this phenomenon that seemingly counters sound solid-liquid equilibrium theory is the focus of this study. The hypothesis is that the conditioning aspect of the oil itself – the act of cooling and preparing the oil in the laboratory – may be causing this to occur. As such particular attention to the cooling coil and bulk fluid temperatures is taken with regards to the samples and their subsequent solubility properties.

Waxy crude petroleum (and in this case, model oils) contains a wide spectrum of paraffinic components (Srivatsava et. al., 1993). WAT or cloud point generally indicates the initial WAT, or temperature that shows the first solid precipitation. However, this is merely one of countless WATs – one for each paraffinic component in the crude mixture, and at each temperature increment more and more compounds precipitate.

Concerning wax crystals themselves, like other crystallization reactions wax crystals give off small amounts of heat being exothermic in nature. Heat must be added to these crystals in order to dissolve them back into solution, leading to a hysteresis between the WAT and wax disappearance temperature (WDT); for crude oils, the WDT is always higher than WAT (Bhat and Mehrotra, 2004). A further source of this hysteresis is the reduced effective surface area for the melting reaction; a rigid crystal has less available reactive surface area than small, free molecules.

The hypothesis arose when observing results during cold flow testing; just as in the study by Bidmus and Mehrotra, we noticed that deposition was completely eliminated in a temperature-controlled test section even when ambient temperatures were several degrees below the flowing oil temperature. The arising hypothesis of this study dictates that the potential source of this anomaly was due to the conditioning or cooling process of the oil.

The oil is subjected to a cooling medium that is colder than the intended bulk fluid target temperature during the cooling process. Heat losses drive this division, and from this division of temperatures a thermal gradient emerges between the surface of the cooling medium – in this case a cooling coil – and the bulk fluid, assumed to be an infinite medium. As oil and pre-existing wax particles pass into this thermal gradient, paraffin precipitation occurs with lower carbon numbers than would normally precipitate at the bulk temperature. Existing crystals and other particulates provide the most favorable nucleation sites, these providing a backbone or support as the crystals reenter the bulk fluid. Due to the hysteresis between WAT and WDT for these new crystals, dissolution does not readily occur, thereby effectively removing these lower carbon number paraffins from the liquid phase of the oil and, more importantly, preventing them from depositing normally under thermal gradients.

We call this hypothesis "Forced Cloud Point Depression", and this study aims to validate this hypothesis, illustrated in Figure 20. In this study a number of filtered samples from a oil at sub-WAT conditions were analyzed and compared to the cooling coil and bulk fluid temperatures. If the hypothesis is supportable, then the WAT of the filtered samples should be found between the coil and bulk fluid temperatures, indicating that the cooling system was indeed affecting the propensity of the cooled oil to undergo deposition as shown by Bidmus and Mehrotra. If the WAT was the same as the bulk fluid temperature, or shows no recognizable pattern or relationship with regard to the bulk and coil temperatures, then this hypothesis would likely be faulty.

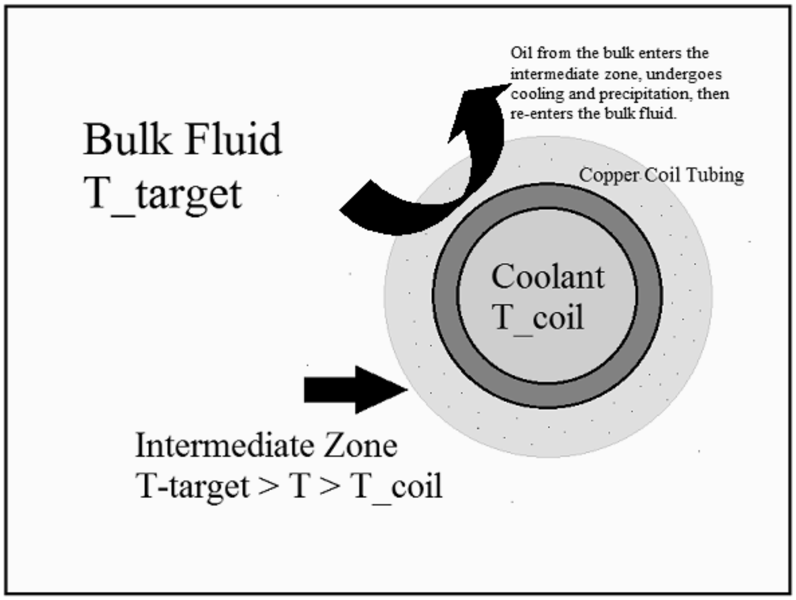


Figure 20: Schematic representation of forced cloud-point depression.

Methods

The experimental setup used is shown in Figure 21. The system used in this study comprised a heat-controlled recycled flow loop, unpressurized, with a large reservoir and custom-designed, clear, acrylic pipe-in-pipe heat exchanger. The pump for the system was a progressive cavity type from Moyno, and heat control was in the reservoir was similar to that of previous studies: a heavy insulator jacket with a quarter-inch copper cooling coil filled with flowing ethylene glycol/water mixture winding through the inner volume of oil. Mixing was done using an IKA mixer motor and 3-inch impeller. All flow lines (with exception of the pump loading lines) were half-inch O.D. stainless steel fitted with Swagelok fittings. The reservoir was chosen to be large in relation to the volume of the flow lines to minimize the effects of wax sequestration due to acrylic section deposition for its original purpose, but for this study it functions well to minimize the effects of sampling. Nevertheless, the oil was checked for initial WAT and gel point after each day of testing to ensure constant fluid properties. Two cooling units – one for the reservoir, one for the acrylic exchanger – were used, these being a programmable Julabo

FP40 and Brinkman-Lauda RM20, both with very high flow rates for maximum efficiency. Cooling medium used was a 50/50 mixture of ethylene glycol and water, plus a mild biocide.

Two types of tests were conducted as part of this study: static and flow. All testing involved cooling the oil under mixing conditions to steady state, sub-WAT and above-Gel Point temperatures; this was achieved by selecting a fixed cooling coil temperature and recording the attributed steady-state bulk fluid temperature. Static tests involve the oil being mixed in the reservoir without any outflow into the flow loop system. The second test, flow, involves having the flow system fully operational with the outflowing oil subject to ambient (25 °C) conditions. This type of test gave a larger spread between coil and bulk fluid temperatures due to heat being added to the flowing fluid from the surroundings. The operational and sampling procedures between the two test types were identical.

Sampling was done using a vacuum filtration method, which was essentially "Cold Filtration" as seen in Figure 21. This "Cold Filtration" system comprised of a Welch DuoSeal vacuum pump connected via hose to a liquid catcher, which in turn was also connected to a special plastic filtration cup fitted with two layers of Whatman Grade 50 Filter Paper (2.3 µm pore size) for complete solids removal. The sealed cup was nearly fully immersed in the reservoir of Figure 21 while sampling. After each test, the entire line was cleansed with warmed acetone to eliminate any traces of oil to prevent contamination.

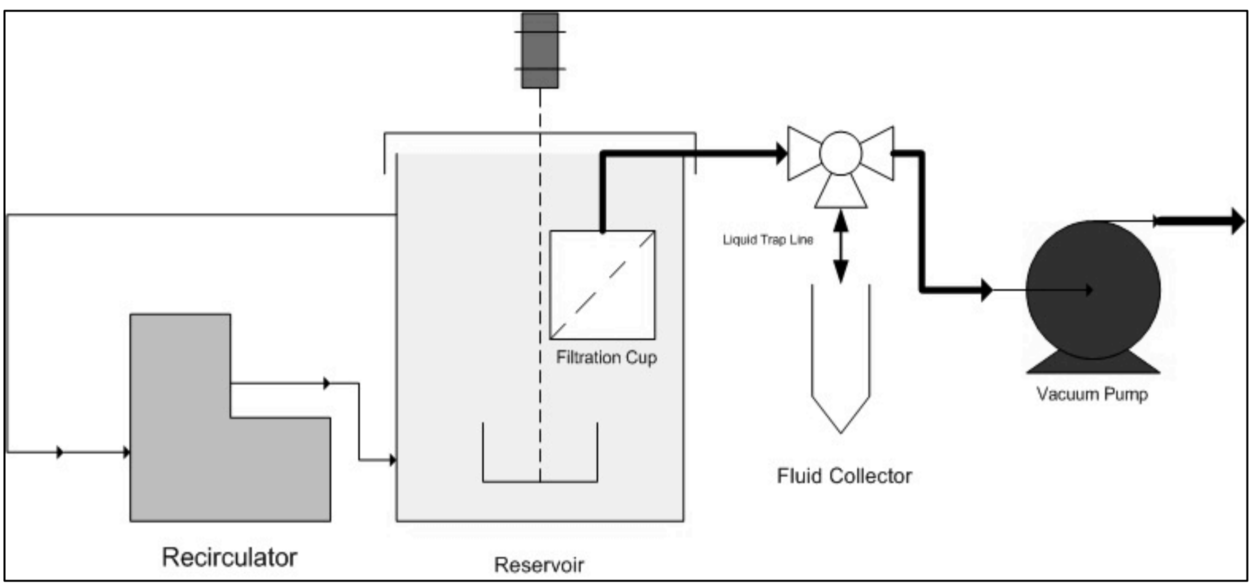


Figure 21: Schematic for the "cold filtration" system. With the filtration cup equilibrated with the reservoir fluid, the vacuum pump engages a -10 psig vacuum pressure against the filter system, drawing fluid up the vacuum line where it is collected in the fluid catcher. Actual position of filter cup in reservoir exaggerated; connection between hose and cup is not submerged, thereby preventing any unforeseen contamination.

To ensure quality samples, the filtration cup was left inside the reservoir for an hour to equilibrate with the steady-state reservoir fluid temperature. Sampling involved creating a vacuum pressure of -10 psig on the filtrated side of the filtration cup, after which fluid would slowly percolate up the filtration path. Vacuum pressure was kept low in these tests to minimize any pressure-driven solubility issues. The filtrate then was required to build inside the vacuum tube until reaching the liquid catch, where 5 mL of sample was collected. It should be noted that the sampling procedure was slow, hence the need for a submersed, equilibrated filter system. As will be shown in Figures 22 and 23, particle sizes were estimated from videos made using an in-flow Canty Vision© cross-polarized camera purchased from J.M. Canty Inc. The particle size distribution for the tests in question ranged from 10 μm at the smallest to over 100 μm; initial testing showed that, even with this particle size distribution, some crystals were making their way through a single filter paper (cloudiness was apparent in the fluid catch), indicating that either some smaller particles existed in the fluid, or particles were being sheared at the filter. Whichever the case, the result was the use of two filter papers to increase tortuosity, and this gave a very satisfactory result and no detectable solids content.

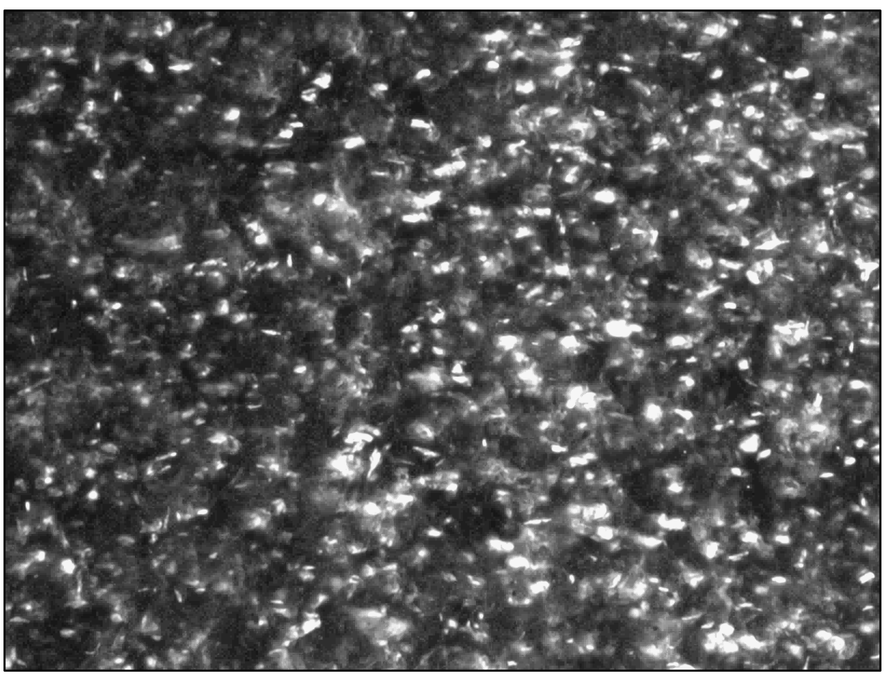


Figure 22: Captured image from live flow video. Cross-polarized light through the Canty Vision camera causes crystals to light up as white shapes in a dark field. Software then measures focused white shapes using determined scaling factors. Particles are largely thin, planar ellipsoids; irregular particles likely two or more crystals stuck together. Flow temperature was 17°C, or 2°C below initial WAT.

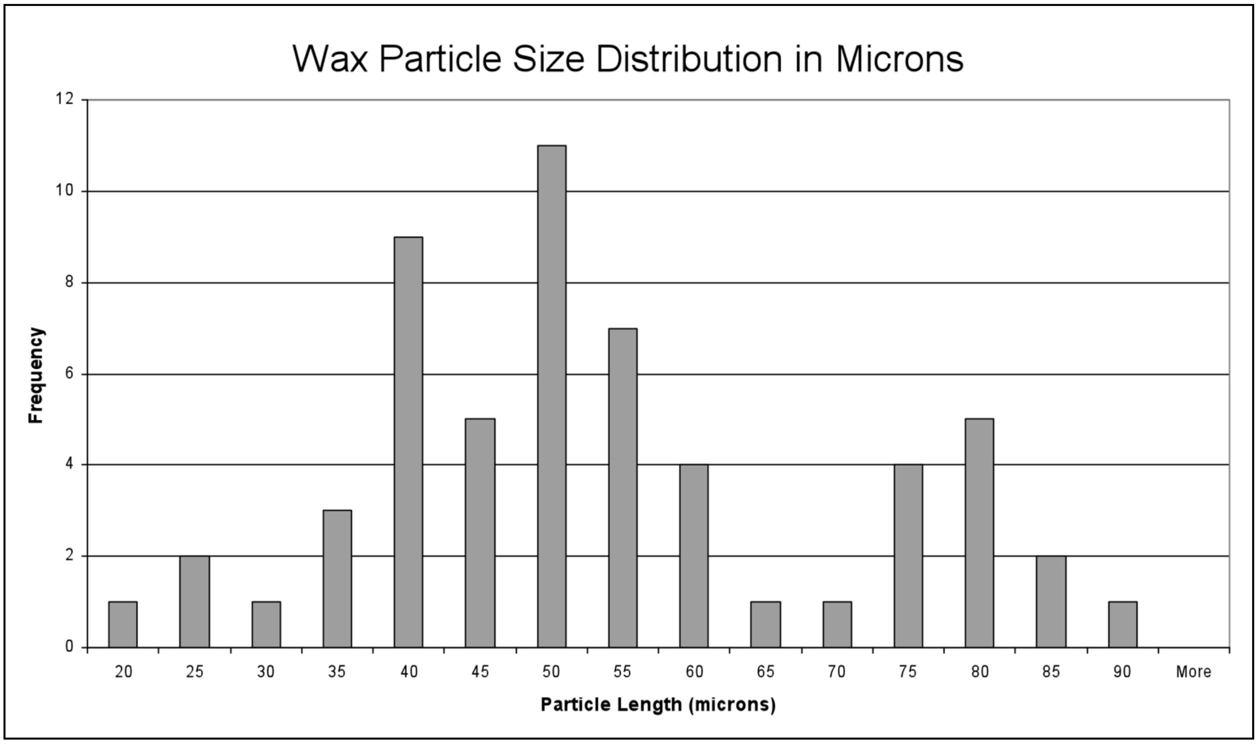


Figure 23: Condensed wax particle size distribution from video source of Figure 22. Note the bimodal nature of the distribution, indicating smaller particles may be sticking together. Particle size distribution supports use of 2.3 µm filter paper; double-layered filtration removed all solids.

The shape of the crystals seen in the flowing system confirm the results of Fogler's group (Venkatesan et. al., 2005; Paso et. al., 2005) which found wax crystals of at least model oils to be ellipsoidal planes in the absence of smaller, high carbon number crystals. Furthermore, the bimodal distribution seems to indicate that clumping or sticking of wax particles is occurring, but that is more a topic for future study and not necessarily applicable to this study.

Sample Analysis

Liquid samples were pulled from the "Cold Filtration" process and were analyzed using the FTIR technique at the University of Utah for WAT analysis. To determine WAT of an oil using FTIR, we followed the method of Roehner et. al., (2001). As a clear fluid cools, its capacity absorbance of particular wavelengths increases with increasing density, but this change is linear with respect to temperature. When phase change occurs – in this case precipitation of wax crystals – the absorbance capacity suddenly increases beyond the fluid density, giving a steeper change in absorbance with respect to dropping temperature. By integrating the area between these wavelengths, plotting the points on a graph (area versus temperature) and extrapolating and intersecting the two slopes linearly as shown in Figure 24 (to the operators best judgment), one can estimate WAT to within reasonable error. An average of multiple runs for each sample was plotted and compared to the coil and bulk fluid temperatures inside the reservoir for the two testing cases; each temperature yielded two samples to improve confidence.

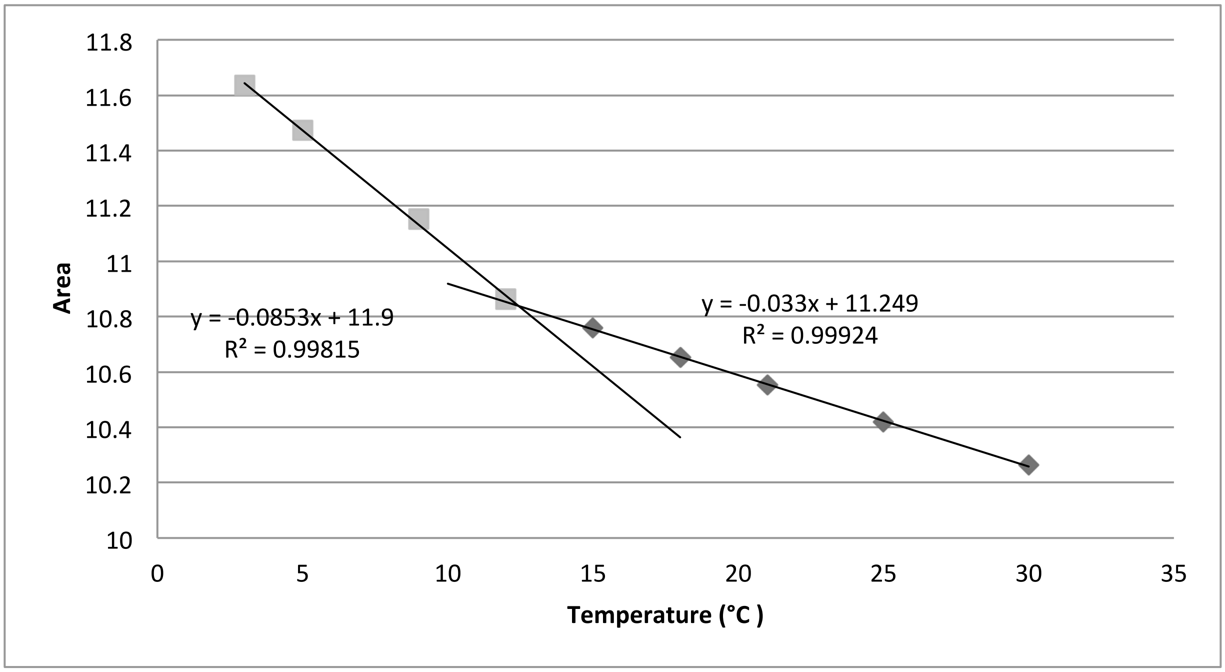


Figure 24: Example of using Roehner et. al.'s FTIR-WAT analysis. This particular static test was run with a coil temperature of 12.0°C and a steady-state bulk reservoir temperature of 12.7°C. The intersection point of the two slopes is approximately 12.4°C. As will be explained in the results section the error is +/- 0.5°C – putting the error beyond the boundaries. This and the other static results led to the conduction of the flowing tests, which give far greater ΔT.

In the case of the filtrate samples, at cooler temperatures one would expect the filtrate to have a lower actual WAT because more wax will have been precipitated in the bulk fluid. To prevent super saturation issues (suppression of solid precipitates due to lack of nucleation sites), the cooling rate from ~10°C above WAT (30°C) to the lower limit of 3°C was set to be 0.1°C/min; cooling from the cooking temperature of 60°C to 30°C was set to be much higher at 1°C/min. WDT is found in the same manner, only while heating the cooled sample. The heating/cooling procedure is shown graphically in Figure 25.

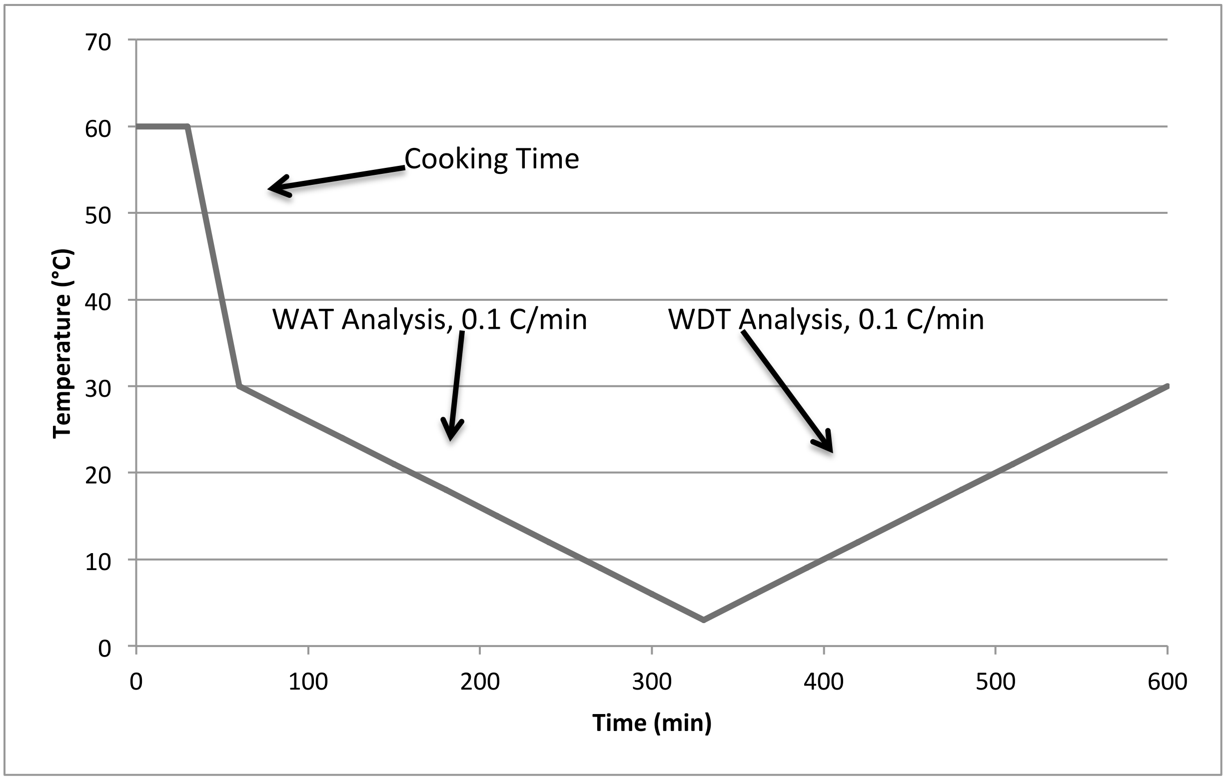


Figure 25. Temperature profile for FTIR testing. Sample is cooled at 1°C/min until 10°C above WAT, after which it is cooled at 0.1°C/min. After the WAT test is complete, the sample is slowly reheated at the same rate and the estimated WDT is found.

The FTIR system used was a Perkin-Elmer Spectrum RXI, with a custom-built, temperature-controlled liquid sample cell. Temperature was maintained using an externally controlled Julabo chiller.

The oil used in this study was a model oil made with three basic components: Chevron Superla-7 Mineral Oil (92.5% by weight), LVGO, Wax (6.0% by weight), and normal paraffinic wax (1.5% by weight). The LVGO wax is a unique blend of lower carbon number isomeric and normal paraffins, having a melting point near 30 °C. The resultant stable mixture gives very desirable solid-liquid equilibrium properties: WAT of 19°C, gel point of 7 °C. Viscometrically the oil is more viscous than typical crudes, but functionally it gives a broad range of sub-WAT testing temperatures – something quite difficult to achieve with simple model oils.

WAT was determined using the Roehner method (Roehner et. al., 2001) with FTIR. Gel point was found using a controlled stress rheometer manufactured by TA Instruments. The gel point procedure was a common and effective cone-and-plate oscillatory sweep of 0.3 Pa at 0.06 Hz frequency, and the gel point itself was determined to be the point at which the storage modulus (G') exceeded the loss modulus (G'') (Venkatesan, 2004). In practicality, this crossing point indicates that a forming gel is resisting deformation rather than being affected by the gentle motion of the cone.

Results and Discussion

Static and Flow tests were conducted with coil temperature ranging from 15 to 6 °C. Table 4 presents a summary of the test results. The next two sections will deal specifically with the Static and Flow results.

Table 4: Summary of the Static and Flow tests using "cold filtration".

Test Method	Condition Name	Coil Temp***	Bulk Temp	WAT**	WDT**
Static	F8	10.0	10.8	10.2	12.4
	F9	10.0	10.8	10.2	13.6
	F10	15.0	15.5	15.3	16.7
	F11	12.0	12.7	12.4	13.9
	F12	8.0	8.9	8.6	11.5
Flow	FL1	15.0	17.4	15.5	18.3
	FL2	13.0	15.9	15.3	16.6
	FL3	6.0	10.1	9.6	10.9
	FL4	10.0	13.5	12.2	13.7
	FL5*	9.6	13.5	12.0	13.6

* FL5 featured a test section jacket of 13.5 C. All other Flow tests with 25 C jacket.
** An accepted error of +/- 0.5 degrees assumed for all data based on FTIR accuracy.
*** All temperatures reported in degrees Celsius.

The results of the Static Method tests are presented in Figure 26. The temperature difference ΔT (bulk-coil) was unfortunately small, being on the same order as the error in WAT measurement. This small difference is due to the excellent insulation of the reservoir that, in other types of experiments, is very beneficial in combating heat loss. In this study, however, it inhibits the confidence in the results. Nevertheless, in all cases the measured WAT values were found to be between the coil and bulk temperatures.

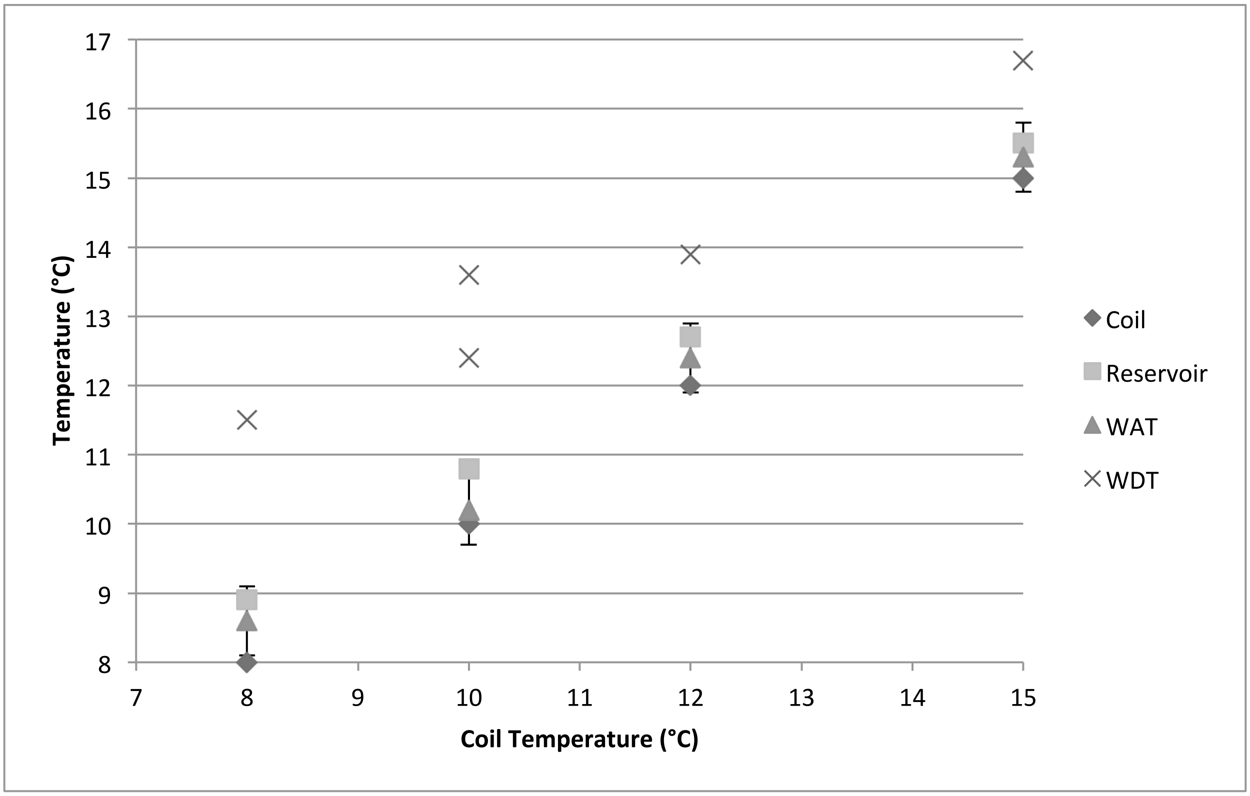


Figure 26. Static method test results. WDT results shown for comparison.

Operating the flow loop while cooling broadened the temperature differential, ΔT, for all tests, giving the resultant WAT values with their corresponding errors a much better resolution. These results are presented in Figure 27. All tests were conducted using a flow rate of 1 gpm through a very-low-shear progressive cavity pump, with test section conditions held at 25°C. As a comparison, test condition FL5 generated samples while holding the test section jacket at 13.5°C to mimic a cold flow condition. The resulting bulk temperature, WAT and WDT appear to be largely unaffected by the change in jacket temperature. Curiously, the coil temperature required to maintain the 13.5°C bulk fluid temperature was lower by 0.4°C than the similar FL4 condition; it is suspected that the ambient temperatures of the summer test may have been slightly warmer than the FL4 condition.

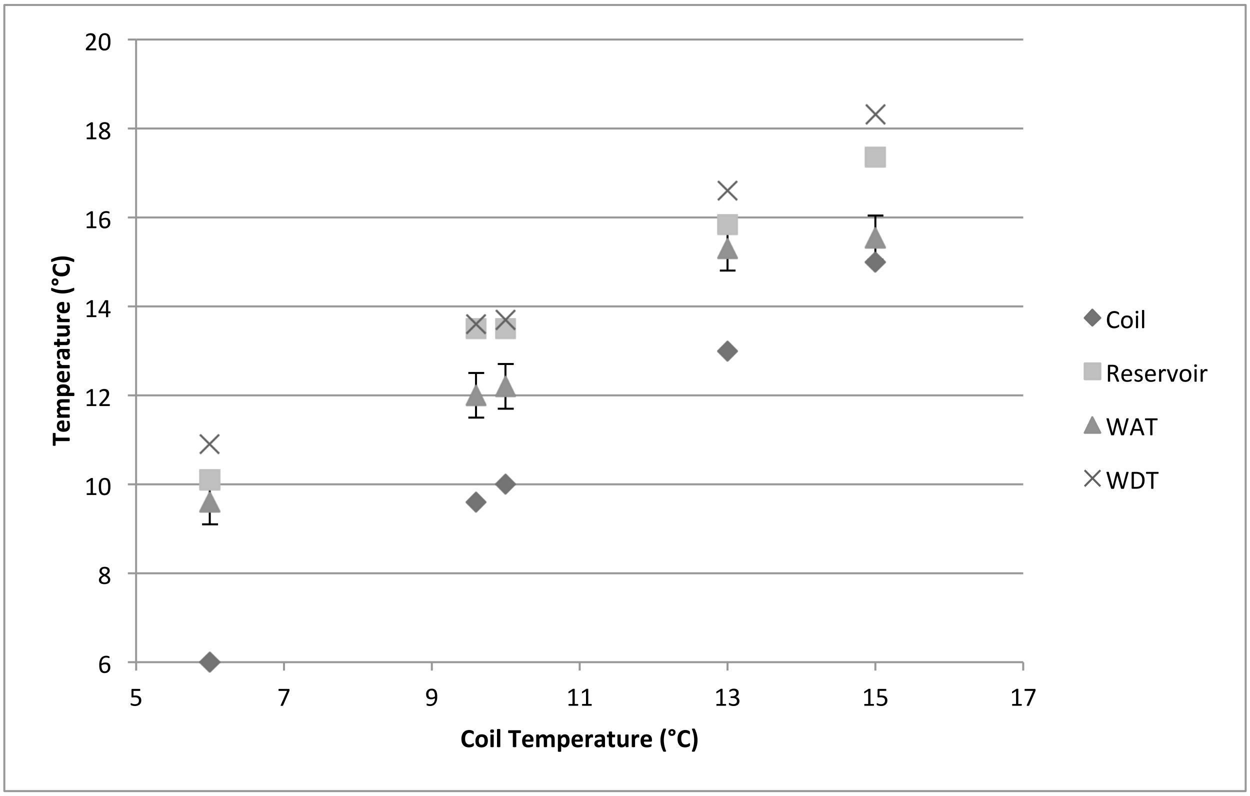


Figure 27: Flow method test results.

While the Static tests conjecturally indicate that the WAT of the filtered samples lies between coil and bulk temperatures, the degree of error and the small difference ΔT is troublesome. The flow tests, on the other hand, very clearly show that, regardless of error, the WAT of the filtered samples is considerably below the bulk reservoir fluid temperatures in all cases.

This study was a qualitative look at a potential source of the cold flow anomaly; the evidence found through this study seems to confirm, at least in part, the forced cloud-point depression hypothesis. While the mechanism of crystallization and the physical parameters and properties are as of yet undetermined, the results show a definite effect of the cooling system on the dissolved paraffin content of the sub-WAT oil. This effect is likely caused by the hysteresis of the wax crystals' solubility; once precipitated, it takes more energy than is present in the system at these testing regimes to melt them back into solution.

A series of tests of both a static and flowing system were conducted at various sub-WAT conditions for a designated model oil. By carefully filtering out wax crystals without heat addition, FTIR analyses confirmed that the actual WAT of the samples, or the temperature at which deposition could occur, was markedly reduced below the bulk oil temperature, especially in the Flow method samples. All tests showed the same pattern – measured WAT values, within error, were found to be between the measured bulk fluid and cooling coil temperatures. This result seems to confirm the forced cloud-point depression hypothesis, which states that the conditioning of oil below initial WAT in a real-world system can reduce the available fractions of paraffin beyond what the operator expects, and this occurrence is due to the hysteresis between WAT and WDT.

While geared primarily towards laboratory studies of crude oils in flow loops, there is a potential industrial application with pipelines. Simply pulling crystals out of solution by flash cooling or other similar method appears to be enough to temporarily block paraffins from deposition. In other words, it may be possible to implement the results of cold flow without actually having to fully reach isothermal conditions. Of course, there is nothing simple about this process on a large scale – particularly in deep-sea conditions.

This study was a preliminary, qualitative look into the phenomenon of cold flow that allows the ambient conditions to be lower than fluid conditions in laboratory flow systems. This effect has been seen in multiple studies using different cooling methods and geometries suggesting that this forced cloud-point depression aspect should be given consideration when designing and conducting slurry-type experiments.

Design, Construction and Testing of a Slurry Maker – A Scraped Heat Exchanger

Purpose

Depletion of paraffin in a laboratory flow system for oils is a problem. The scraped exchanger functions as a means of cooling a waxy oil below its wax appearance temperature while removing wax deposits from the cooling medium by means of a rotating blade. This allows for a slurry to be made automatically without the need for manual deposit removal, and can facilitate slurry-oil experiments of all types.

Design

The scraped exchanger consists of a pipe-in-pipe heat exchanger; the inner pipe is two inches in diameter and twenty-two inches in length; the outer tube is shorter than the inner tube, fourteen inches in length and four inches in diameter. The tubes are centered both axially and radially, and welded together using two cut annular plates to completely separate the inner and outer chambers. The ends of the inner tube have a lip attached to allow a clamp seal; this clamp seal holds the end pieces to the main structure. The end piece consists of an oil seal that keeps fluid inside the inner tube while allowing the scraper shaft free rotation. The scraper blade has a shaft length five inches greater than the inner tube, allowing it to be fixed to a low-speed motor. The blades are set in a vane pattern – four blades set perpendicular to each other – with the length of the blades being one quarter inch longer than the outer tube; this allows the blades to scrape the entire cooling surface plus a tolerance of one eighth of an inch on either end. The blade tolerance is kept to several thousandths of an inch; while not perfectly flush, tests have shown this to be sufficient in removing wax buildup. Holding the shaft in place are two simple bushings, and for higher pressure testing shaft seals can be placed internally. Fluid ports are placed counter-currently, with outlets pointing up for gas removal.

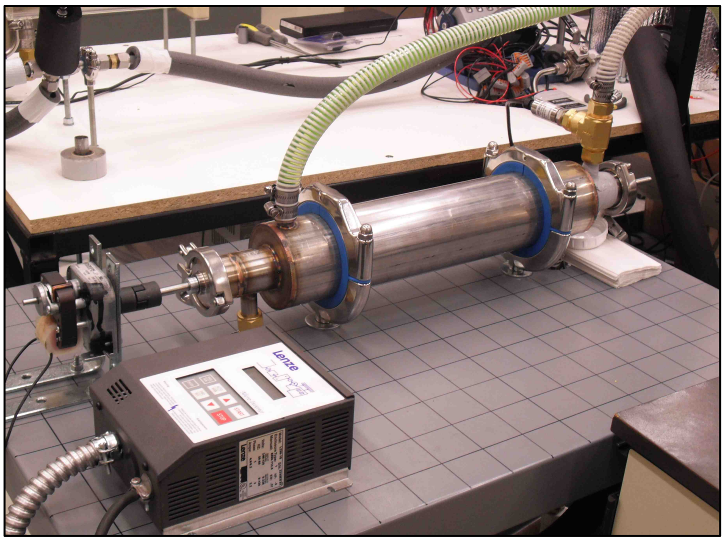


Figure 28: Scraped exchanger system. Exchanger, motor, and pump (not shown) all mounted on a single cart for ease in access and portability. Exchanger is hooked to a large reservoir (also not shown) allowing for sufficient flow.

Results

While testing the scraped exchanger, one looks for two factors: 1) does it successfully remove wax from the cooling wall, and 2) does it successfully make a slurry? To test (1), we attached pressure transducers to the inlet and outlet of the oil side (inner tube). While operating the coolant (outer tube) at a cold temperature well below the oil's pour point, we then pumped oil through the scraped exchanger at around one and a half gallons per minute while monitoring the pressure difference between the two transducers once the oil reached a steady-state temperature. If the scraped exchanger failed at removing wax, we noted a marked increase in the pressure drop (noted primarily in the inlet transducer) while fluid conditions remained the same. While some deposit was naturally expected due to the tolerance, this amount was very small and had a very minimal effect on pressure drop and fluid properties overall. It was suspected that should a failure take place, it would be due to wax buildup on the blades themselves.

Figure 29 shows the pressure difference between the two transducers over time after the oil reached a steady state temperature of several degrees below its WAT. The periodicity seems to indicate some buildup occurred, but once it reached a certain height the blades swept away the entire deposit (This sweeping was likely due to the cohesive strength of the wax deposits.):

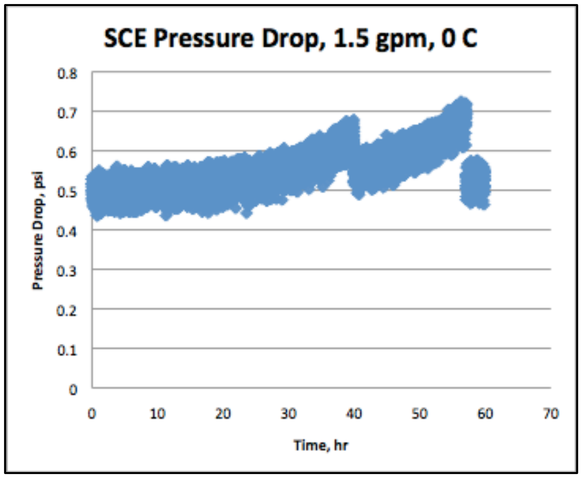


Figure 29: Periodicity of pressure difference in Scraped Exchanger indicates wax buildup being removed. Removal is marked by sudden drops to the original, clean-wall condition.

To test (2) – the slurry-making potential of the scraped exchanger – we conducted a visual check of the fluid itself, as well as a restart test. Visually checking the fluid condition using a clear acrylic pipe-in-pipe heat exchanger positively confirmed slurry presence (cloudy, opaque fluid). The restart tests were more interesting, however, as they showed that shutting in and forming gel from a slurry as opposed to a clean oil loading condition resulted in a much weaker gel – one that also broke through the center as well as at the wall (result confirmed visually with recorded images). These restart tests were conducted in both acrylic and normal stainless steel test sections and gave virtually identical results under identical cooling rate and final temperature (cold flood refers to the cooling mechanism, in this case flooding the test section with a pre-cooled coolant); the WAT of this oil is 19°C; note the sudden drop in gel strength.

Cold Flow Restart

Purpose

The question of cold flow restart was brought up at the industrial steering committee. It would be necessary on occasion to shut down a pipeline undergoing cold flow slurry transport. The experiments performed in this section were designed to determine restart requirements under these conditions and compare them with the hot flow conditions.

Procedures

The cold flow restart test began first by establishing cold flow. The procedure is enumerated below.

1. Set coolant for desired test section to be just above WAT (21°C).
2. Set reservoir mixer to 460 RPM to ensure good mixing and as uniform a crystal size as possible.
3. Set coolant for scraped exchanger (conditioning loop) to be ~15°C below desired oil temperature (e.g., for an oil temp of 15°C, set the coolant for scraped exchanger to 0°C).
4. Open valve to scraped exchanger pump; turn on pump to ~2-3 gpm based on Hertz table.
5. Open main flow line valves and turn on main pump to ~1 gpm.
6. As fluid temperature drops below WAT, lower the test section coolant temperature to be about 2°C higher (e.g., if oil is at 18°C, set jacket to 20°C); continue to lower jacket temperature as fluid cools.
7. Once desired oil temperature is reached, adjust the flow rate as desired and begin lowering the jacket coolant temperature to match the oil temperature.
8. Lower jacket temperature to 0.1°C cooler than oil temperature to account for heat losses along coolant lines.
9. Begin monitoring pressure drop across test section for duration of test; steady increases in pressure drop indicate the presence of deposition (This can be easily confirmed using clear test section.).

The cold flow restart experiments were conducted using the following procedure.

1. To conduct a "cold flush" cooling method, switch test section coolant to unused exchanger (e.g., flow coolant through unused steel section instead of clear section) at final, sub-pour point cooling temperature (e.g., 4°C). Test section being used will not experience deposition since WAT of the oil is below room temperature, thus simulating cold flow.
2. Prepare oil using "cold flow" steps 2-5.

3. Once oil reaches steady state, desired conditions, turn off the main pump, wait a few seconds for pump motion to cease, and close entrance valve to test sections.
4. Immediately switch test section coolant line from the unused to the active test section.
5. Begin monitoring pressure; values should remain around 0 psig (unpressurized system) while fluid is kept in place using the riser to the reservoir.
6. After desired aging time (oil reaches final temperature quickly) of at least three hours, slowly open the entrance valve; if valve was closed too quickly earlier, the pressure pulse can break the gel, so care is required.
7. With the pump off, adjust the speed dial to the preselected rate (very low speed for ramping).
8. Turn on pump, monitor pressure drop for upstream transducer peak; this peak marks the yield pressure, which should be significantly lower than similar restart pressure for a clean, non-slurried oil under the same cooling rate and final temperature.
9. To conduct a constant-cooling-rate restart test, the "cold flow" steps 1-7 can be followed; once at conditions, shut down flow, close entrance valve, and set test section coolant temperature to sub-pour point temperature; the cooling rate is 0.33°C per minute by default, and can be manipulated to be slower.
10. Restart will be the same as "cold flush" method.

Results

Cold flow restarts were conducted at different cooling temperatures, and using the clear and the steel loops. The restart pressures were compared to those observed for restarts after shutdown above the WAT. Results are shown in Figure 30. In both the cases, reduced restart pressures are observed when restart under cold flow conditions is implemented. This shows that the gel formed in the presence of slurry may not be as uniform and strong. Visualization of breakup in the clear section restart showed that the gel breakup for a gel obtained by cooling above the WAT was always a wall failure, while the break in cold flow restart often occurred as "core" failure or breakage in the gel in the central portion.

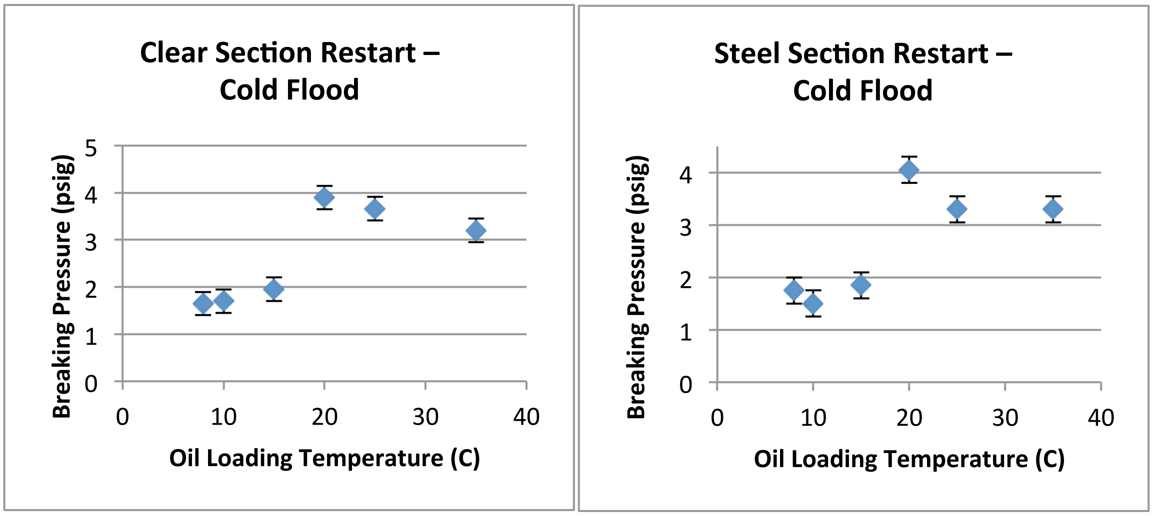


Figure 30: Restart pressure below the wax appearance temperature is significantly reduced from clean condition under identical test section cooling rates (about 0.5°C per minute) and final temperature (4°C).

Removing the gap between the blade and the inner tube wall could improve cooling rates inside the scraped exchanger, since the small wax buildup that formed (as shown earlier in Figure 29) impeded heat transfer. The current cooling rate was near 0.083°C per minute; while this matched field cooling rates quite well, the ultimate goal of the scraped exchanger study was to design a system that cooled oil rapidly in harsh conditions, allowing it to enter transit lines in slurry conditions.

Modeling Cold Flow

The University of Utah undertook wax deposition modeling using the commercially available software PVTsim/DEPOWAX provided by CALSEP A/S in order to gain insight into relative values associated with thermodynamics, and heat, mass, and momentum transport connected with wax deposition. Specifically, the existing DEPOWAX model for wax deposition was used to help design laboratory scale flow-loops, and the PVTsim thermodynamic model was used to evaluate anticipated solid-liquid-equilibrium for potential model oil systems.

Modeling of Hypothetical 8" Gulf of Mexico Oil Pipeline

In order to understand some of the issues surrounding hypothetical cold flow in a simple oil pipeline, a eight-inch (8") pipeline carrying oil in the GUM was modeled using DEPOWAX. The oil was assumed to be a Garden Banks condensate previously described by Hernandez Perez (2002), initially above 110°F. The pipeline was assumed to carry 40,000 BPD, and to consist of an eight-inch internal diameter five-inch wall thickness steel pipe that was nine miles in length. Temperature outside the pipe was assumed to be 37.5°F ambient (sea water) and the pipe had a 10 BTU/hr ft^2°F heat transfer coefficient.

Figure 31 shows that without cooling the oil to create cold flow, a large ΔT exists between the oil and seawater over the length of the pipeline, which in turn results in high levels of deposition in a seven-day period due to thermal diffusion of liquid paraffin molecules to the relatively cold pipe wall, as shown in Figure 32. An additional mechanism for wax deposition initially identified but perhaps undeservingly named shear dispersion by Burger et. al. (1981) creates the hump in the wax deposition curve once the oil reaches a temperature below 95°F. Significant amounts of precipitated wax carried by the oil are available for deposition, as shown in Figure 33.

The DEPOWAX model predicts significantly less deposition for drastically reduced starting oil temperatures, and no deposition if there is no ΔT present between the oil and sea water. The validity of this calculation is important since we found no deposition even in the presence of small thermal fluxes. These calculations also identified conditions of shear at the pipe wall relevant for subsea pipeline systems, which would need to be created in laboratory-scale flow-loop systems.

Initial Conceptual Modeling of ½" Laboratory Flow-loop

The DEPOWAX model was also used to evaluate conceptual ideas for a half-inch (½") laboratory flow-loop using the same GOM oil as a test fluid. This modeling gave insight into possible flow rates, fluid temperatures, and testing times needed to obtain reasonable measurements for scaled conditions. The modeling also identified a reasonable size for recirculation tanks to avoid depletion of paraffin in the test fluid. Table 5 summarizes some for these calculations performed with DEPOWAX.

Table 5: Summary Table of DEPOWAX modeling results for ½" flow-loop concept.

DEPOWAX Calculation Summary - Proposed UoU 1/2" Flowloop Test Matrix 1 foot long Test Section

Oil: Garden Banks Condensate (GOM Oil) per O. Perez M.S. Thesis, University of Tulsa, 2002 used for oil.

Test Description	Oil GPM	Calculated Reynolds No.	Calculated Wall Shear (1/sec^-1)	Oil Temp (F)		Calculated Wall Temp. (F)	Ambient Temp (F)	Test Period (hr)	Calculated Wax Deposit (mm)	Calculated Deposit Vol. (cm^3)	Comments
				Inlet	Outlet (Calc)						
Laminar - Hot Oil	1.41	1372	275	95.00	94.8937	52.18	37.5	24.0	0.63	9.22	Deposit is 80 wt.% oil
Turbulent - Hot Oil	2.82	2751	915	95.00	94.8435	80.12	37.5	24.0	0.28	4.17	
Laminar - Cold Oil	2.76	1111	461	38.00	37.9998	37.64	37.5	24.0	0.06	0.96	
"	"	"	"	"	"				0.01	0.17	k*=0, so diffusion deposition only
Turbulent - Cold Oil	5.52	2221	1526	38.00	38.0000	37.64	37.5	24.0	0.20	3.03	Barely Turbulent…very very small DT for fluid.

Notes:

1.) An overall outside heat transfer coefficient of 10 BTU/hr ft^2 F is assumed similar to subsea heat transfer rates.

2.) A k* value of 2.5E-9 lb/ft^2 is assumed in the PVTsim DEPOWAX model (for solid wax agglomeration deposition) per Burger & Perkins 1981 JPT paper….this drives the estimate of low temp, low DT deposition.

Exceot for the one model run with k* set to zero to see diffusion mechanism only.

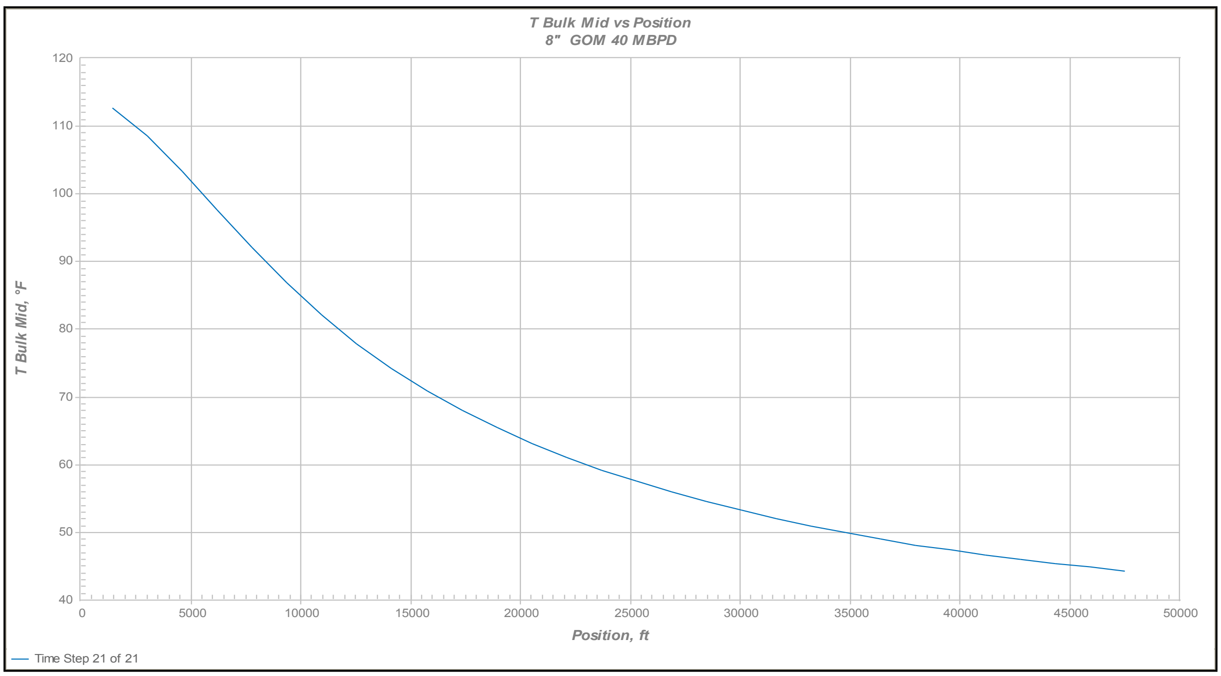


Figure 31: 8” GOM oil pipeline bulk oil temperature vs. length.

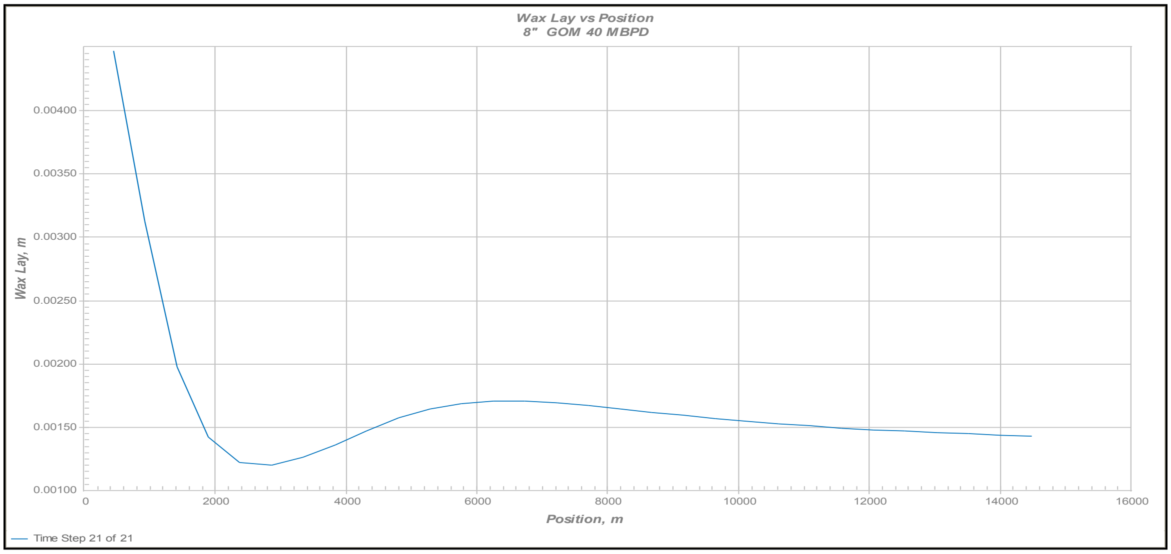


Figure 32: Wax deposition in 8” GOM oil pipeline.

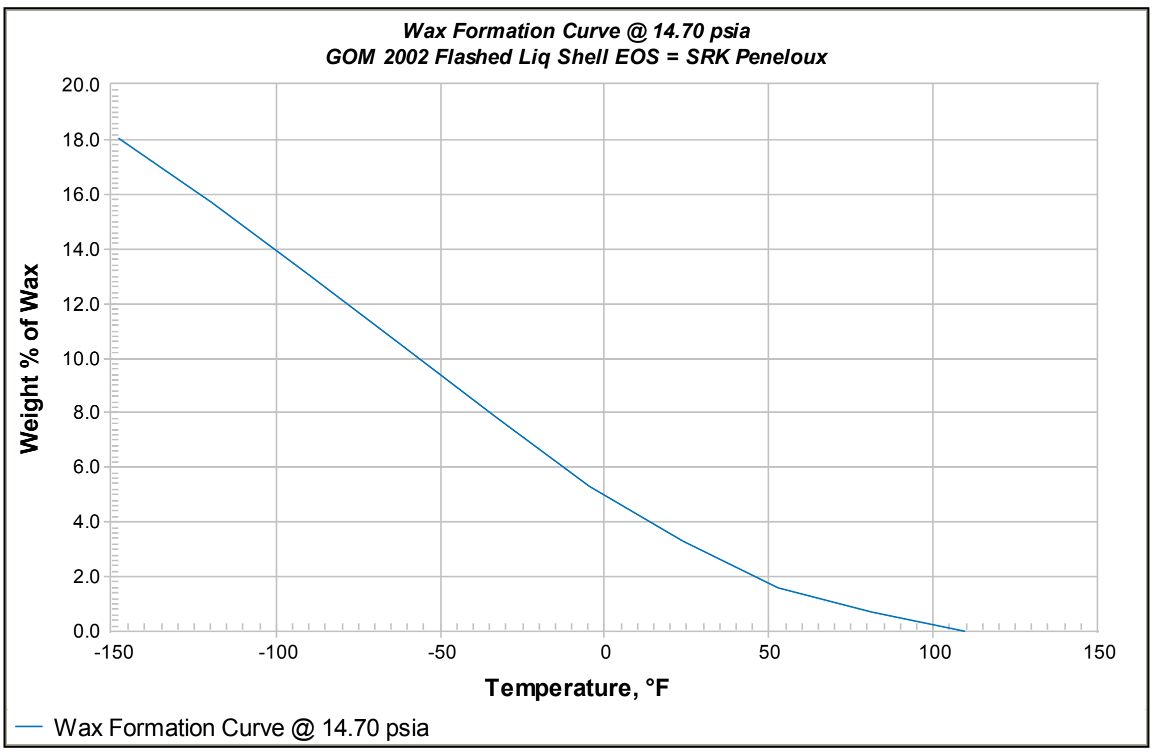


Figure 33: Wax precipitation vs. oil temperature for GOM oil in Example 8” oil pipeline.

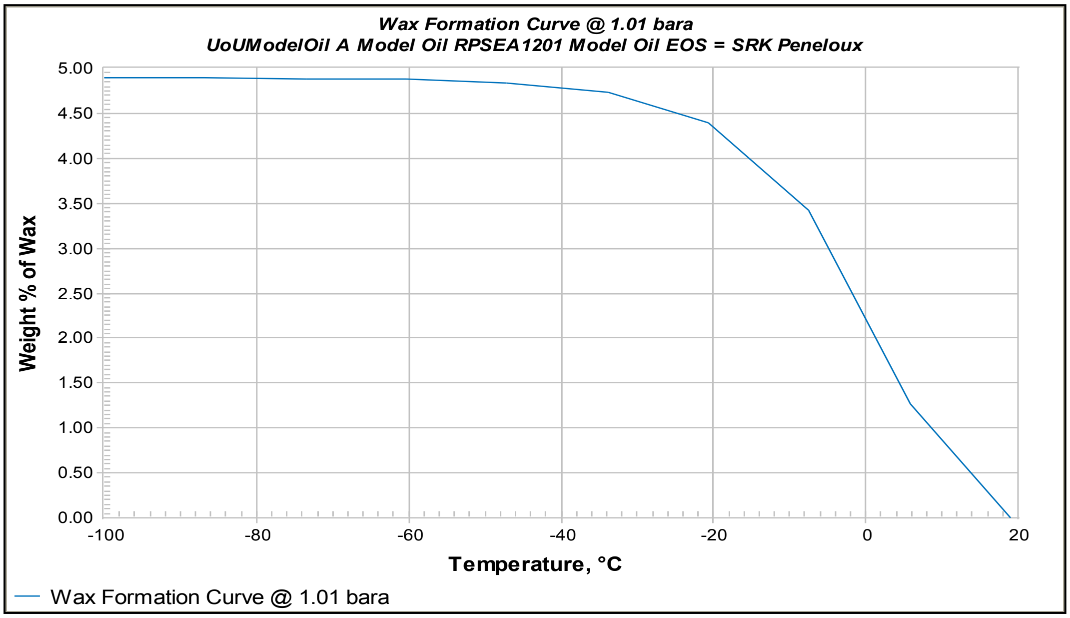


Figure 34: PVTsim estimation of model oil wax precipitation curve.

Laboratory Flow-loop Simulation

As the design and operation of the laboratory flow-loop system was completed for initial test runs, some exploratory modeling of anticipated test conditions was undertaken using DEPOWAX to confirm desired test parameters for the specific model oil system (1.5 wt% wax, 5wt% LVGO, 93.5 wt% SUPERLA) to be used. In addition, a key estimation needed was the anticipated wax precipitation curve for the model oil, since the slope of the curve and relative values are believed to be critical to understanding the driving force for deposition present in the system. Figure 34 provides an example wax precipitation curve generated by PVTsim for a model oil considered for use in the experimental effort. The experimental values obtained for the oil are shown in Figure 35.

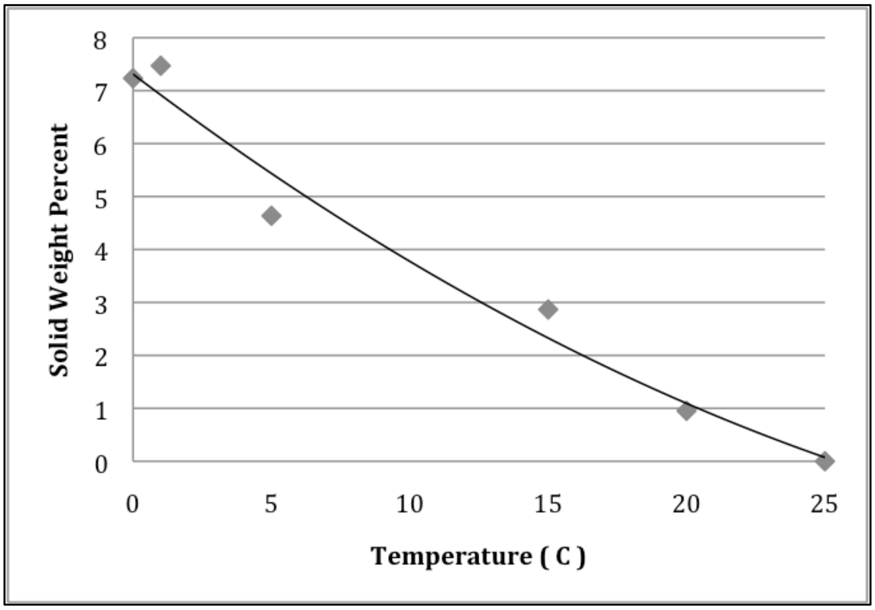


Figure 35: Experimental weight percent of solids precipitated versus temperature using the FTIR method proposed by Roehner and Hanson (2001).

Conclusions

This study was conducted to assess the effectiveness of technologies for using uninsulated single subsea tiebacks or export lines so that marginal fields can be produced economically. The first part of the study consisted of a literature review of available technologies for preventing or remediating primarily wax deposition problems. The literature review revealed that there was sufficient evidence that cold flow, a technology in which the oil is cooled to ambient temperature (which in the case of GOM fields was about 2-4°C), is effective in minimizing both wax and hydrate deposition. The review also revealed that selected chemical intervention is necessary and pigging capability will always be needed as a backup strategy.

The experimental plan consisted of evaluating the effectiveness of the cold flow technology for minimizing wax deposition. Hydrate-related experiments were not performed because the industrial steering committee indicated that the time and resources available for the project would not be adequate to perform both wax and hydrate evaluations. The first step in the evaluations was the design of the model oil system. Model oil was used in all experiments to ensure reproducibility and consistency. The model oil was designed to have sufficient separation between the wax appearance temperature and the pour point. Composition of the oil and its properties were established.

A novel cold flow system with a flow section and conditioning loop was designed, and two loops were fabricated – a clear loop and a steel loop. An essential component of design was a slurry maker or a scraped heat exchanger. This was fabricated and tested. The particle sizes were measured using a particle visualization system.

A number of cold flow tests were performed at various thermal fluxes, flow rates, and solids loading. Negligible amounts of deposits were recorded using pressure drop measurements and were visually confirmed in the clear loop. Thus, the feasibility of cold flow was demonstrated. While performing these experiments, it was evident that small thermal flux also did not lead to significant deposits. One possible reason for this was the cloud point depression that was caused by the precipitation and deposition of wax in the reservoir. This hypothesis was tested and proven. This has implications on how cold flow must be implemented in practical applications.

One of the concerns when using cold flow is the uncertainty surrounding restarting when a pipeline with oil and slurry is shut down. The restart process under cold flow conditions was compared with the restart process in conventional shutdowns (oil temperature starting above the wax appearance temperature). It was shown that the restart pressures for cold flow were lower than those under conventional conditions, and core failures were possible with cold restart.

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